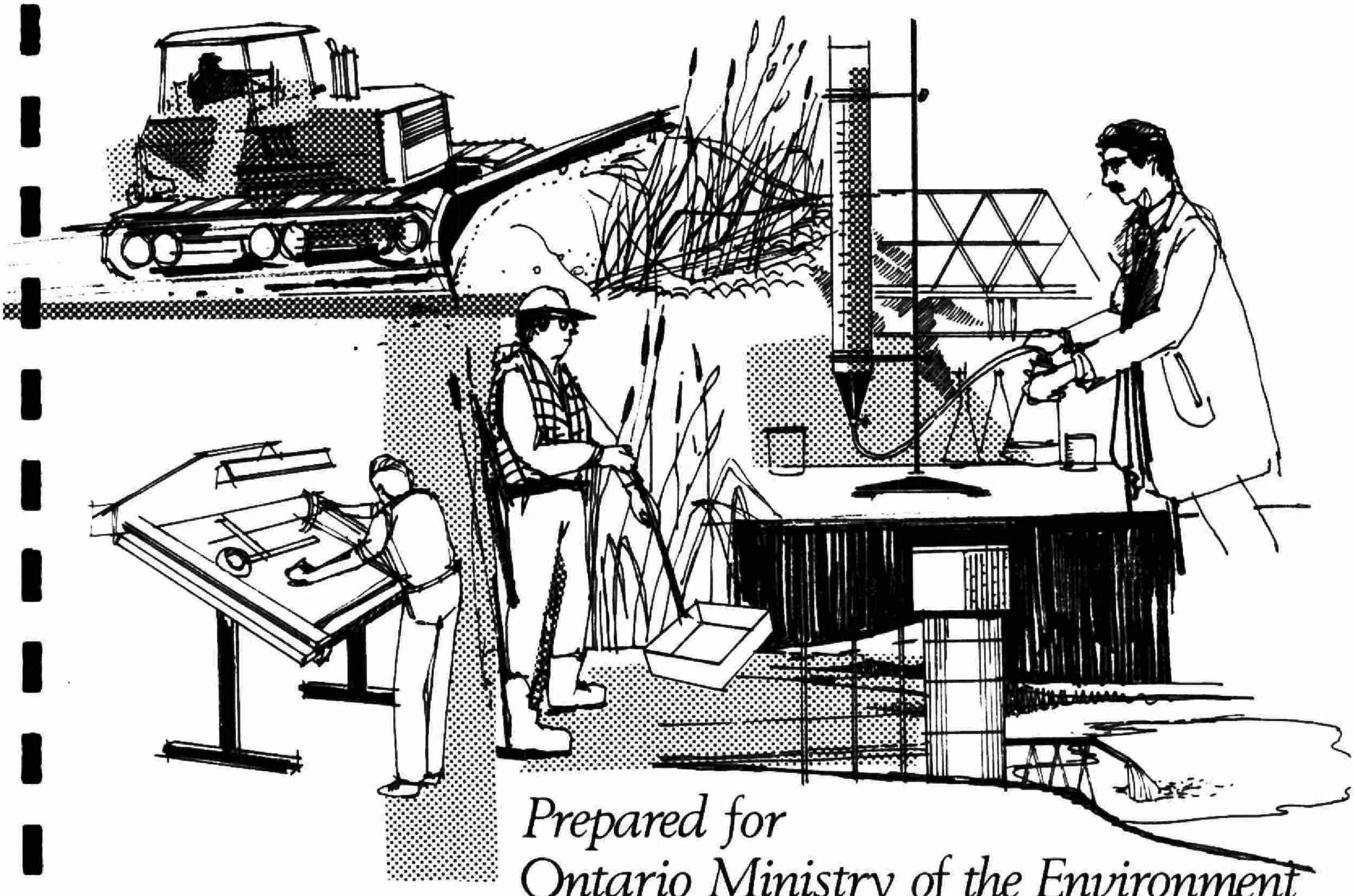
Heavy Metal Mobilization and Bioavailability — Cobalt Mine Tailings



Prepared for
Ontario Ministry of the Environment

Prepared by
J E Hanna Associates Inc.
IN ASSOCIATION WITH
Institute for Environmental Studies, University of Toronto AND *Golder Associates · October 1984.*

T A B L E   O F   C O N T E N T S

LIST OF TABLES

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

This study was supported through funds provided by the Research Advisory Committee of the Ontario Ministry of the Environment.

The original concept arose through the discussions with **Mrs. I. Wile** of the Hazardous Contaminants Branch, Ontario Ministry of the Environment. She was responsible for the research and development of artificial marsh sewage treatment technology in Ontario and has maintained an ongoing interest in the Cobalt project. The knowledge and experience that she offered in the study design were a fundamental reason for its success.

Mr. Gordon Miller of the Timmins District Office, Ontario Ministry of the Environment was responsible for supervising the work and gave freely of his practical knowledge throughout the study. His cooperation and support are gratefully acknowledged.

A number of organizations and individuals made major inputs to various components of the study.

Institute for Environmental Studies,
University of Toronto.

Dr. Pamela Stokes, Director of the Institute, supplied a wealth of knowledge concerning the biology and biochemistry of heavy metal mobilization and uptake. She also played a significant role in coordinating many of the various laboratory experiments and analyses which were required.

Ms. Mary Agnes Balicki operated the ICP Analyzer and despite a seemly endless and unpredictable assortment of samples and the idiosyncrasies of the machine remained calm and unflustered and efficiently carried out the work that was necessary.

Mr. Mat Hilgerdenaar provided equipment and space for the leaching apparatus. In addition his experience in operating similar experiments proved valuable in dealing with the details of constructing the leachate collection system.

Golder Associates

Mr. Stan Feenstra was responsible for coordinating the geohydrology component of the work. His extensive practical experience in dealing with tailings were valuable for the efficient and reliable conduct of this component. He also critically reviewed the overall results and report.

Mr. Rob Blair installed the piezometers in the field and undertook the hydrological tests. He also prepared the notes on the mining history of the area and the chemical characteristics of the minerals being mined.

JE Hanna Associates Inc.

Mr. Edward Hanna was responsible for directing the overall study and conducted much of the data analysis.

Mrs. Rysa Hanna coordinated the field sampling components and undertook most of the onsite investigations.

Ms. Lauren Crooks collected the tailings cores for the laboratory experiments, documented the characteristics of the tailings and conducted the physical analysis of the samples.

Mr. Bert von Rosen assisted in the field sampling program, prepared many of the field samples for analysis, oversaw the submission of samples and receipts of results and did much of the initial data manipulation.

Mr. Ed Oikawa conducted the leaching column experiments. He was responsible for the actual performance of all components going from the set up of the apparatus fo final preparation of the samples for analysis.

Mr. Jim MacFarland diligently through rain or shine recorded groundwater levels in the onsite piezometers, collected groundwater samples and exhumed litter bag samples periodically.

Mrs. Soile Hamalainen entered reams of numbers into the computer, typed this manuscript, put up with repeated and often questionable changes to the text and worked the extended hours needed to complete the study.

The results of this study are the combined efforts of the above team of people and each was essential to completing the work successfully.

1.0 INTRODUCTION

1.1 RATIONALE

This project addresses an identified problem and one which could arise in the near future. The known problem is that of contaminant leaching from mine tailings in particular heavy metals (Down and Stocks, 1977). Associated with this leaching is the potential for pollution of both ground and surface waters with effects on both the health of people drinking the water and on other biological organisms in the environment. Considerable effort has been directed to controlling contaminant leaching from tailings but a detailed understanding of chemical mechanisms of contaminant release and biological uptake is lacking (Jenne and Luoma, 1978).

The tailings in the Cobalt area are unusual in that they are quite alkaline although a large range of heavy metals in relatively high concentrations are present. The neutralization of acid tailings is a common initial step preceding vegetative reclamation. The Cobalt tailings offer an opportunity to examine the behaviour of heavy metals and biological uptake in a quite different chemical environment from the more typical acid tailings associated with sulphide ore bodies. Concomitantly, the mitigation techniques applicable to alkaline tailings may well differ substantially from those suitable for acidic wastes.

The second potential problem which this project addresses is imminent and relates to an ongoing project funded by the Ontario Ministry of Northern Affairs and coordinated by the Ontario Ministry of the Environment. Two experimental artificial marshes which receive municipal sewage effluent have been constructed at Cobalt to test the feasibility and performance of this technology; one marsh is built on tailings. If the systems are effective, a full-scale marsh will be built to treat sewage from Cobalt.

The primary focus of the experimental marsh is on the treatment of sewage; however, changes in the groundwater and soil chemical regime, in addition to the introduction of marsh biota on the tailings, may significantly alter the mobility and bioavailability of contaminants.

The investigation of these types of effects are beyond the current program for the channel marsh project but relate specifically to the interests and priorities of the Ontario Ministry of the Environment. This research has two direct and specific applications, first to the management of the extensive tailings in the Cobalt area and second to the design and operation of the artificial marsh sewage treatment system. General application of the results to environmental management of tailings and to contaminated leachate treatment by wetlands is also possible.

1.2 STUDY OBJECTIVES

The overall study objective was:

> **To determine the mobility and bioavailability of heavy metals* in mine tailings under varying moisture and chemical regimes.**

These results are of direct relevance to tailings management in particular in the Cobalt area. Specifically, the study was intended to derive estimates of:

i) Current leaching rates and biological uptake of contaminants under varying edaphic conditions;
ii) Potential changes in leaching rates and biological uptake of contaminants from tailings due to nutrient enrichment that could result if a full-scale artificial marsh system was constructed;
iii) Changes in leaching rates and biological uptake of contaminants that can be expected with disturbance to the tailings;
iv) Probable effects of mitigation strategies such as revegetation, altering water tables, and chemical treatments on leaching rates and biological uptake of contaminants.

---

* The term "heavy metals" is used through the text and includes some elements which strictly speaking are not heavy metals (eg, arsenic) but which are typical toxic elements in tailings.

1.3 SCOPE

The Cobalt area was selected as a study area for two reasons. First the ongoing experimental work with artificial marshes provided an excellent opportunity to examine how leaching rates and bioavailability might change over the short and long term with elevated water tables and altered water chemistry. Second, Cobalt is surrounded by a large number of tailings disposal sites varying in size, site conditions, and to some extent, age. This range in conditions offered an excellent basis to examine variations in heavy metal mobilization.

The factors examined were:

i) soil moisture
ii) nutrient status/biological activity
iii) disturbance history.

Specifically, four sites were selected which represented the following conditions:

i) dry, vegetated, unenriched (site 2);
ii) wet, vegetated, unenriched (site 1);
iii) wet, vegetated, enriched (site 3);
iv) recently disturbed and flooded, vegetated, enriched (site 4).

The primary focus of the study was on the chemical and biological mechanisms affecting metal mobility and the bioavailability of labile forms.

The soil chemistry component concentrated on variations of contaminant concentrations and mobility vertically through the tailings under different soil saturation and leaching water chemistry conditions. The analysis consisted both of field sampling and laboratory experiments using lysimeters.

The biological analysis consisted of three components. The first consisted of analysis of native vegetation to determine contaminant burdens. Bioavailability was tested in the laboratory using duckweed (Lemna minor). Finally, biological release of metals during decomposition was examined by means of in situ litter bags.

From a hydrological perspective the major emphasis was on defining directions of surface and ground water flow and water table conditions based on field measurements. Ground water samples were analyzed for chemical constituents and heavy metal concentrations. These were related to hydrological conditions and laboratory results.

2.0 SITE CHARACTERISTICS

2.1 LOCATION AND SETTING

Cobalt is located on Highway No. 11 approximately 140 km north of North Bay (Figure 1). It is one of the three towns in the "Tritown" area, the other two being New Liskeard and Haileybury.

The Town was established just after the turn of the century when a silver deposit was discovered. Mining has remained the primary industry. The current population is about 3,000 and like many northern communities, this number fluctuates significantly according to the vagaries of the economy and the yield of the mines. Currently, mining activity in the Town is at a low point.

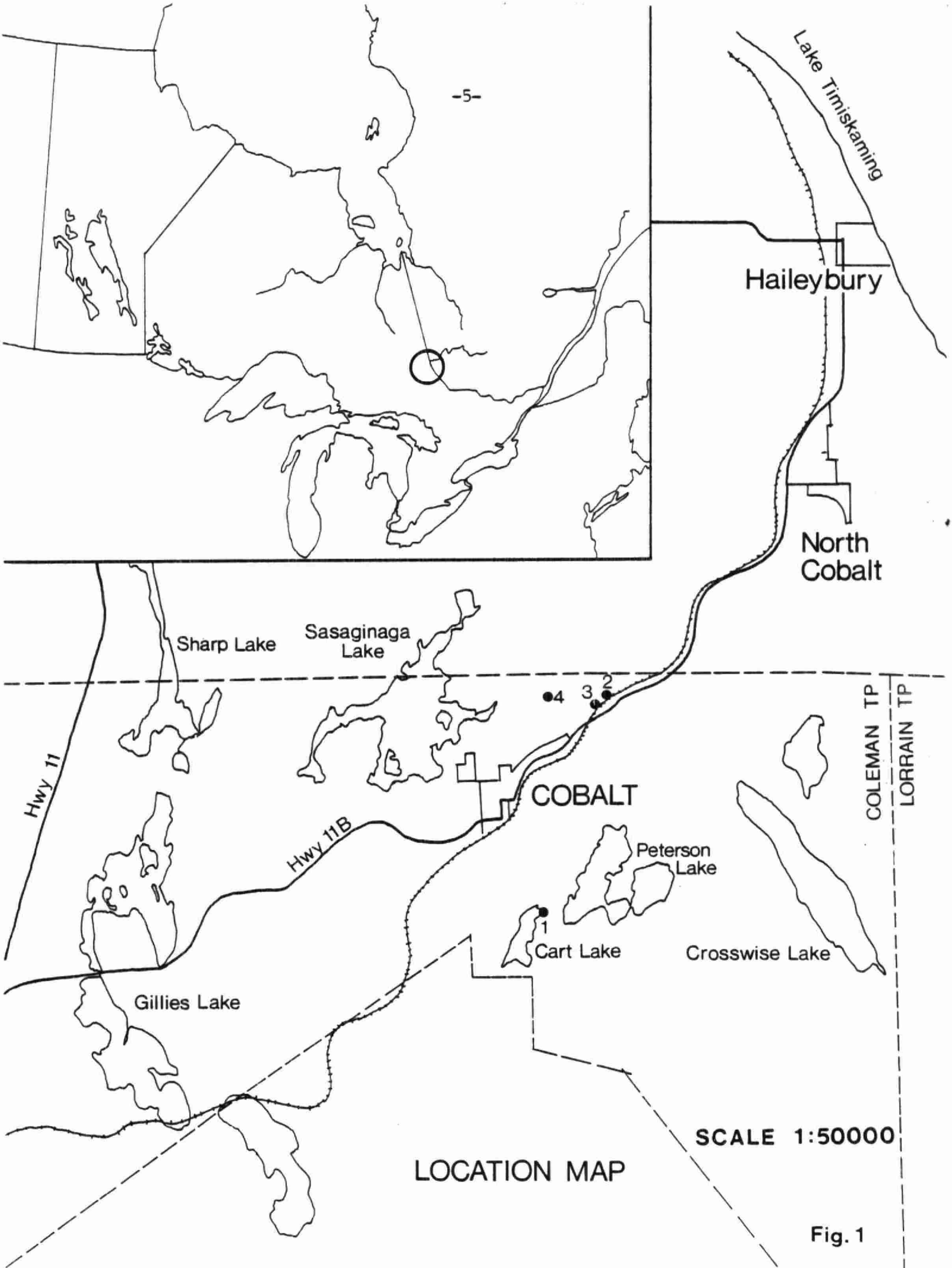
The population is serviced by municipal water supply and sewer systems. The sewers outfall at two locations and directly enter a stream system that flows out of the Town to the southeast. The watercourse ultimately discharges into Lake Timiskaming.

2.2 ENVIRONMENTAL CONDITIONS

2.2.1 Climate

Cobalt is well removed from the influence of any large waterbodies and experiences relatively extreme variations in temperature over the year. It located in the Timiskaming Clay Belt Climatic Region (Chapman and Thomas, 1968); this region "is separated from the Sudbury region on account of its shorter and moister growing season and its colder winters" (ibid).

Table 1 provides some basic climatic statistics for the Cobalt area. These figures indicate the extreme variations in temperature which occur.



LOCATION MAP

Fig. 1

Table 1 Select Climatic Statistics for Cobalt Area (Source: Chapman and Thomas, 1968).

Mean Annual Temperature	2.8°C
Mean Annual Minimum Temperature	-39.5°C
Mean Daily Temperature: July	18.0°C
January	-14.5°C
Mean Length of Growing Season	176 days
Mean Number of Frost Free Days	90 days
Mean Annual Precipitation	327 cm
Mean Annual Snowfall	223.5 cm

2.2.2 Vegetation

The site falls within the Temagami Section of the Great Lakes - St. Lawrence Forest Region (Rowe, 1972). It lies close to the border of the Haileybury Clay Section but is located on the adjacent Precambrian Shield Uplands. Most of the vegetation is in a transitional state due to extensive disturbance from logging, fire, and mining activities.

Vegetation components of both the Boreal and Great Lakes - St. Lawrence Regions are present with the former being most frequent and common on wet lowland sites and the latter in drier upland conditions.

The drier tailings support limited vegetation (ie, between 0 and 50% cover). The older tailings generally support the most extensive vegetation. Also wet conditions and nutrient-enriched runoff (ie, sewage waters) stimulate more growth (ie, between 50 and 100% cover) than the drier unenriched conditions. The dominant taxa are Equisetum, Juncus, Populus, Salix and Typha (see Chapter 4 for a detailed account of the native vegetation).

2.2.3 Physiography

Cobalt is situated within the Southern Province of the Precambrian Shield. The bedrock is primarily part of the Gowganda Formation which consists of conglomerate, sandstone and siltstone (Card and Lumbers, 1975). Surficial deposits consist of a discontinuous layer of ground moraine deposited during the last glacial episode 8-10,000 years ago (Boissonneau, 1965). The soil is clay in texture with frequent cobbles and boulders.

Local relief varies up to 30 m locally and on average the area lies about 290 m ASL. The irregular terrain is typical of the Shield with frequent bedrock outcrops and local wet areas in depressions. There are a number of lakes in the area with the major drainage system being the Montreal River.

2.3 MINING HISTORY AND ORE PROCESSING

Silver was discovered at Cobalt in 1903 and mining has been continuously carried out since 1904. Currently, Aqnico Eagle is the only active producer. Teck Corp. recently shut down its mine in the spring of 1983. Sulpetro is carrying out a tailings reprocessing program of old tailings at the north end of town.

The ores mined at Cobalt consist of carbonate veins mineralized with native silver plus cobalt-nickel and bismuth arsenides, and iron-copper and lead sulphides. The principal gangue in the ore is calcite and the host rocks are chloritic, siliceous sediments of the Gowganda Formation, and intrusive chloritic greenstone and Nipissing Diabase.

Mineral processing of these ores is a purely physical process including grinding and heavy mineral segregation by both shakers and flotation. This process removes most of the native silver, sulphide and arsenide minerals. The tailings consist of carbonate gangue and host rock. The concentration of silver and heavy metals in the tailings varies, tending to be lower in the recent tailings because of the increased efficiency of modern processing.

The tailings are characteristically dark greenish grey in the coarser-grained sand fraction and become lighter in colour as the grain size decreases. Tailings sedimentation is typical of most tailings basins; the fine fraction or 'slimes' tend to settle in a distal location to the outfall in contrast to the coarser sand tailings.

Of the tailings examined in the Cobalt area, no evidence of hydroxide crusts, extensive vegetation kills or discoloured surface water, typical of acid generation, were noted. All ages of tailings were observed and the vegetation seems to have taken a relatively strong natural hold on much of the tailings' surfaces.

3.0 STUDY DESIGN

The research consisted of essentially two components, i) field sampling and ii) laboratory experiments. The emphasis was on the latter component although each served an essential role. This section describes the design and conduct of each component of the research project.

3.1 FIELD SAMPLING

Four types of field studies were conducted: i) ground water levels; ii) surface and ground water chemistry; iii) vegetation species composition, abundance and metal loads; and iv) litter decomposition and metal release. Each of these are described following.

3.1.1 Site Selection

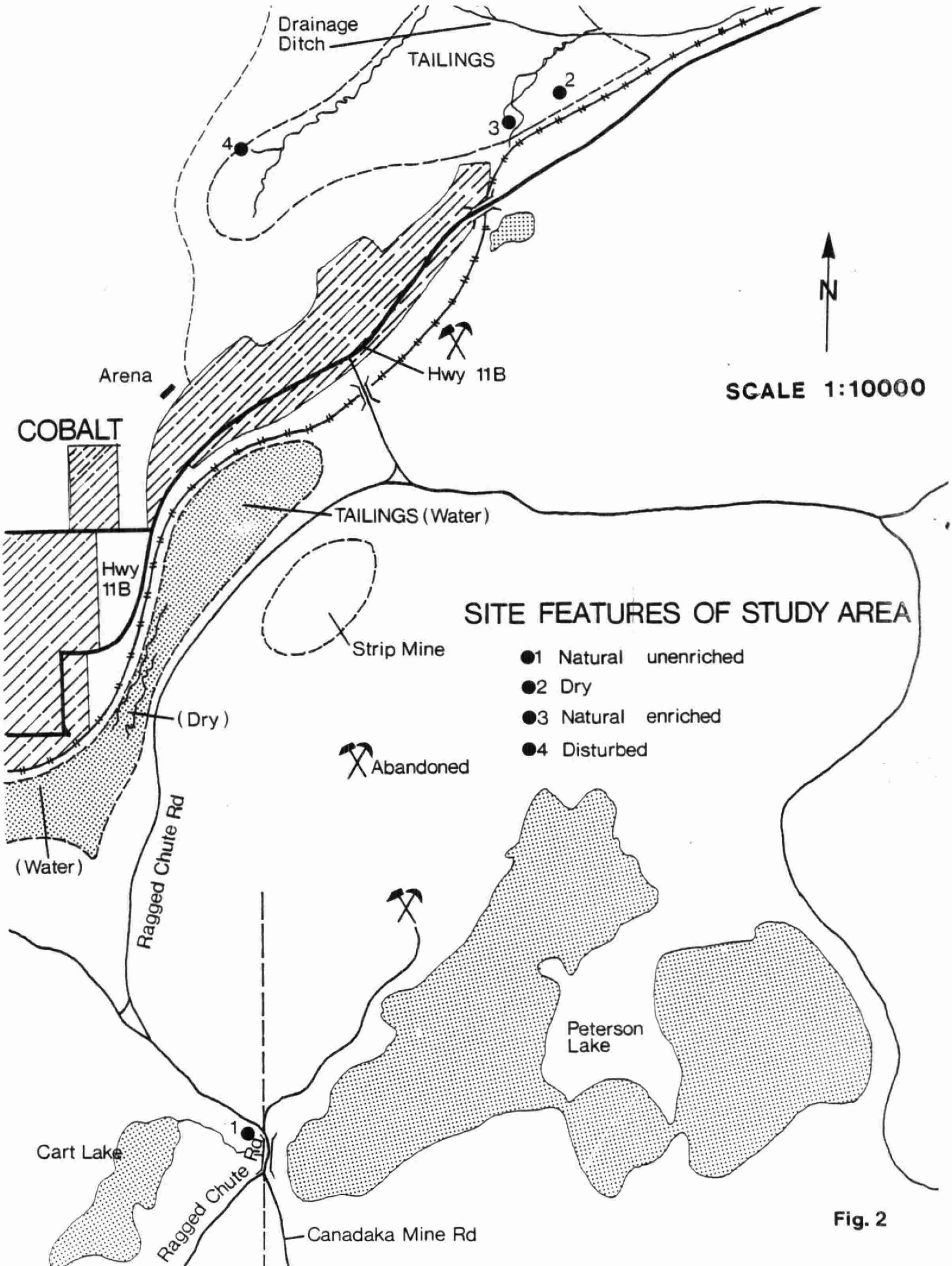
Four sites were selected to represent each of the environmental conditions to be investigated (see Section 1.3). A number of locations was examined and those selected best represented key environmental factors and were the least likely to exhibit anomolous characteristics due to local disturbances or edge (transitional) effects (Figure 2).

The sites were first located using aerial photographs and the final selection was made by E. Hanna and G. Miller in October 1983 based on field observations. A 10m x 10m plot was marked by corner posts and located precisely on topographical maps and air photos.

3.1.2 Ground Water Monitoring

At each site, series of piezometers were installed. They were constructed of 4.5 cm PVC tubing with a drive point affixed to the end. Generally a nest of 3 was installed at varying depths (1-3m) to determine vertical gradients. One or more piezometers were located radially from the central nest based according to expected groundwater patterns. The elevations of the top of each piezometer and the ground surface were measured by a controlled survey.

At the time of installation, pumping and recovery tests were used to estimate hydraulic conductivities.



Drainage Ditch
TAILINGS
2
3
4
Arena
COBALT
Hwy 11B
SCALE 1:10000
N
TAILINGS (Water)
Hwy 11B
SITE FEATURES OF STUDY AREA
Strip Mine
●1 Natural unenriched
●2 Dry
●3 Natural enriched
●4 Disturbed
(Dry)
Abandoned
(Water)
Ragged Chute Rd
Peterson Lake
1
Cart Lake
Ragged Chute Rd
Canadaka Mine Rd

Fig. 2

Water levels in the piezometers were recorded using a standard electrical resistor tape on a biweekly interval from May to mid August. The water level records obtained from these piezometers were used to map horizonal groundwater flow.

3.1.3 Water Sampling

Surface and ground water samples were collected, (note: those to be used for metal analysis were acidified with concentrated nitric acid) and analyzed for each site (Figures 3, 4, 5, and 6). Grab samples from streams in or adjacent to the plots were collected in October 1983 and July 1984.

Groundwater samples were collected from shallow and deep piezometers using a peristaltic pump and filter. The procedure was

i) pump each piezometer dry
ii) allow water level to rise to former level
iii) collect 250 ml sample
iv) filter sample and acidify if required
v) store in cool location until analysis.

Three sets of groundwater samples were collected over the growing season which represented various watertable levels and antecedent weather conditions.

3.1.4 Vegetation Inventory

The vegetation inventory was directed at i) characterizing species composition and dominance; ii) estimating standing biomass; and iii) determining metal burdens in dominant species.

Species composition was measured using a standard random quadrat procedure. In each plot, ten 0.25 m^2 quadrats were analyzed. The number of stems of each species present were enumerated and overall percent cover estimated. In addition, a running list of species present in each 10 m by 10 m plot was maintained.

Standing biomass was calculated by recording the average height of each dominant group of species in each quadrat. A representative sample of the height classes of these species was collected, dried in the laboratory and the dry weight measured. These curves provided a basis for estimating species biomass dry weight from the height measurements.

Metal burdens were estimated by collecting representative fresh samples. These were then dried, digested and analyzed for metal content as described in Section 3.2.2.

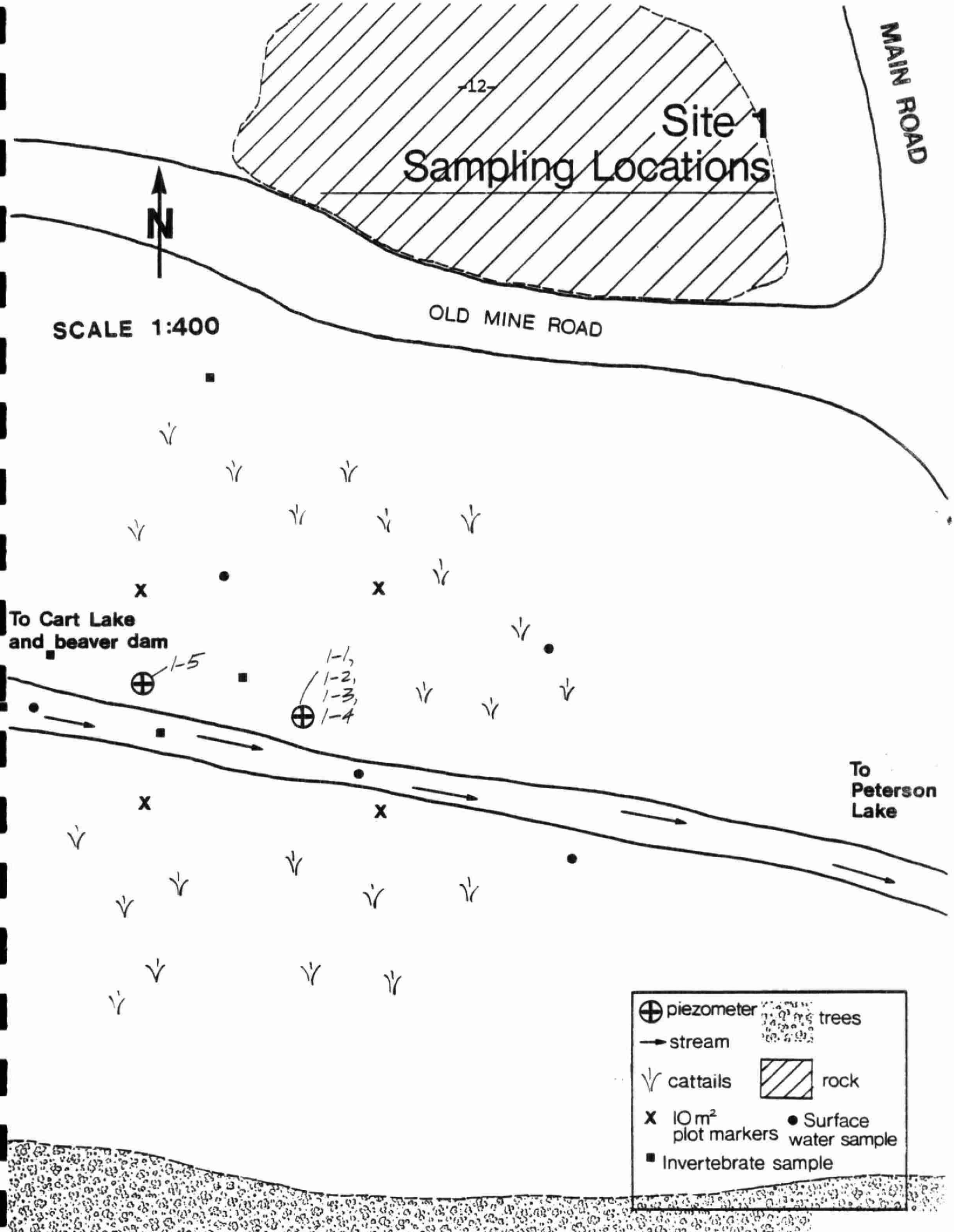
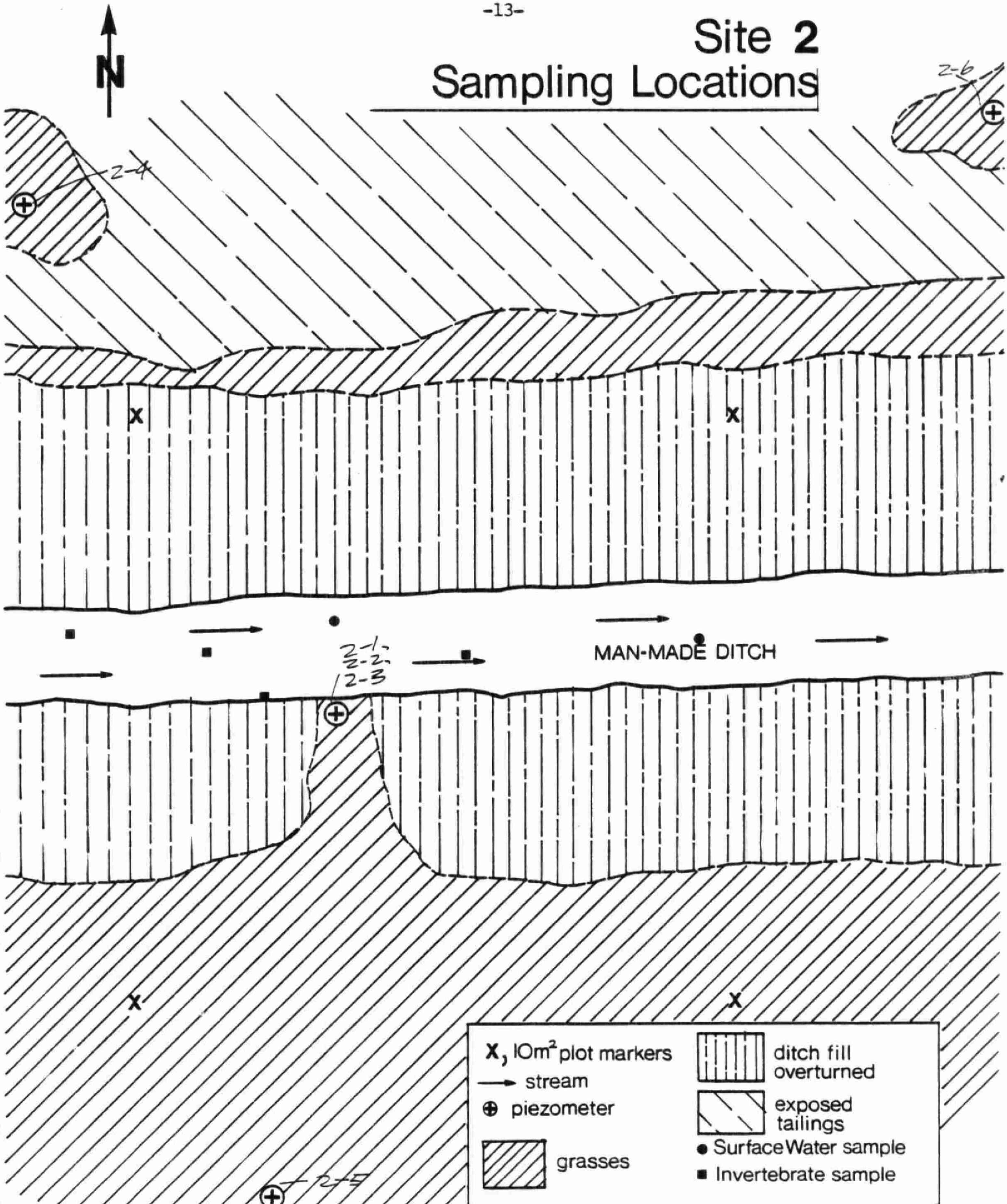

Site 1
Sampling Locations
MAIN ROAD
N
SCALE 1:400
OLD MINE ROAD
To Cart Lake
and beaver dam
1-5
1-1,
1-2,
1-3,
1-4
To
Peterson
Lake
piezometer
trees
stream
cattails
rock
10 m²
plot markers
Surface
water sample
Invertebrate sample

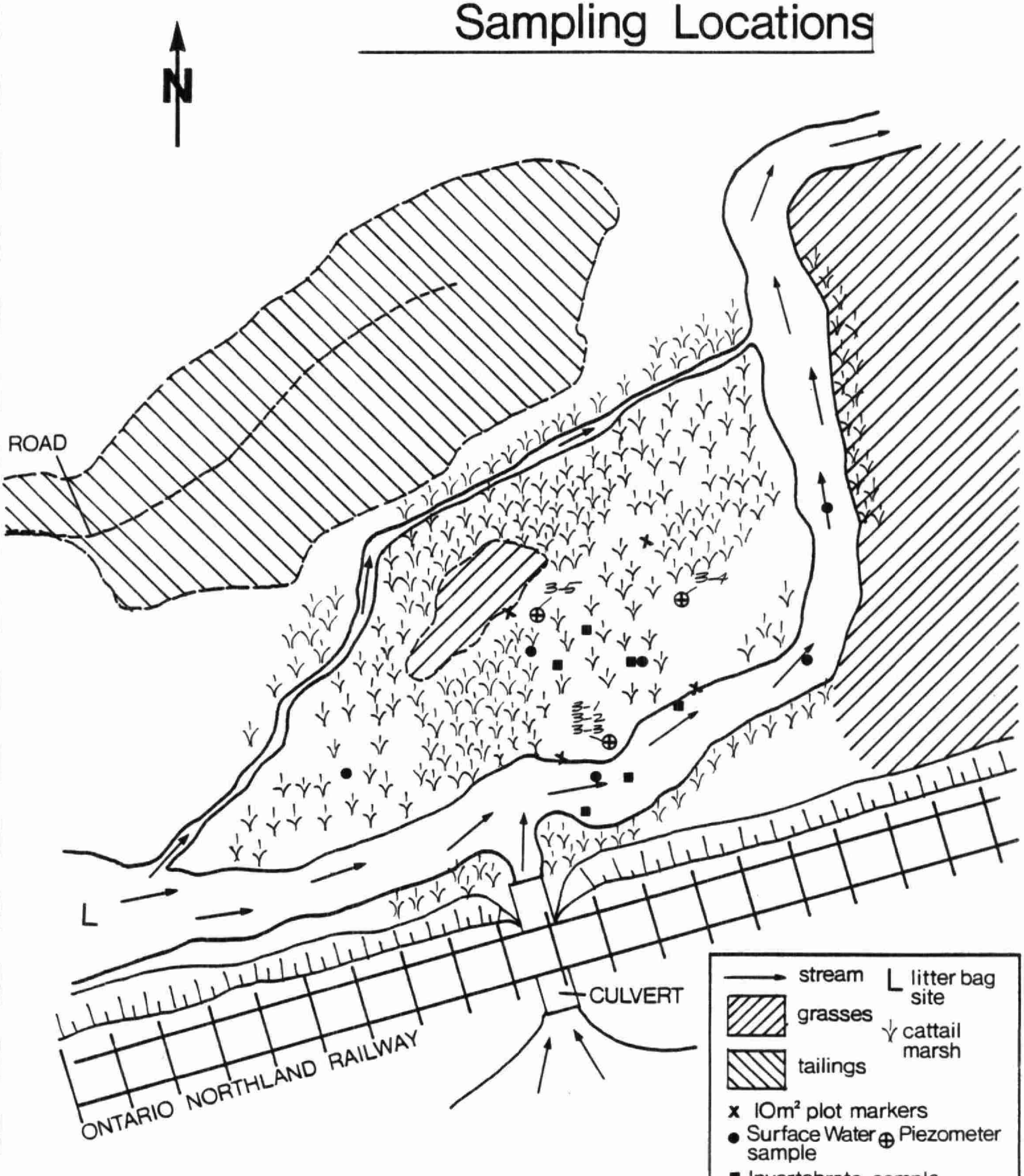
Fig. 3



SCALE 1:200

Fig. 4

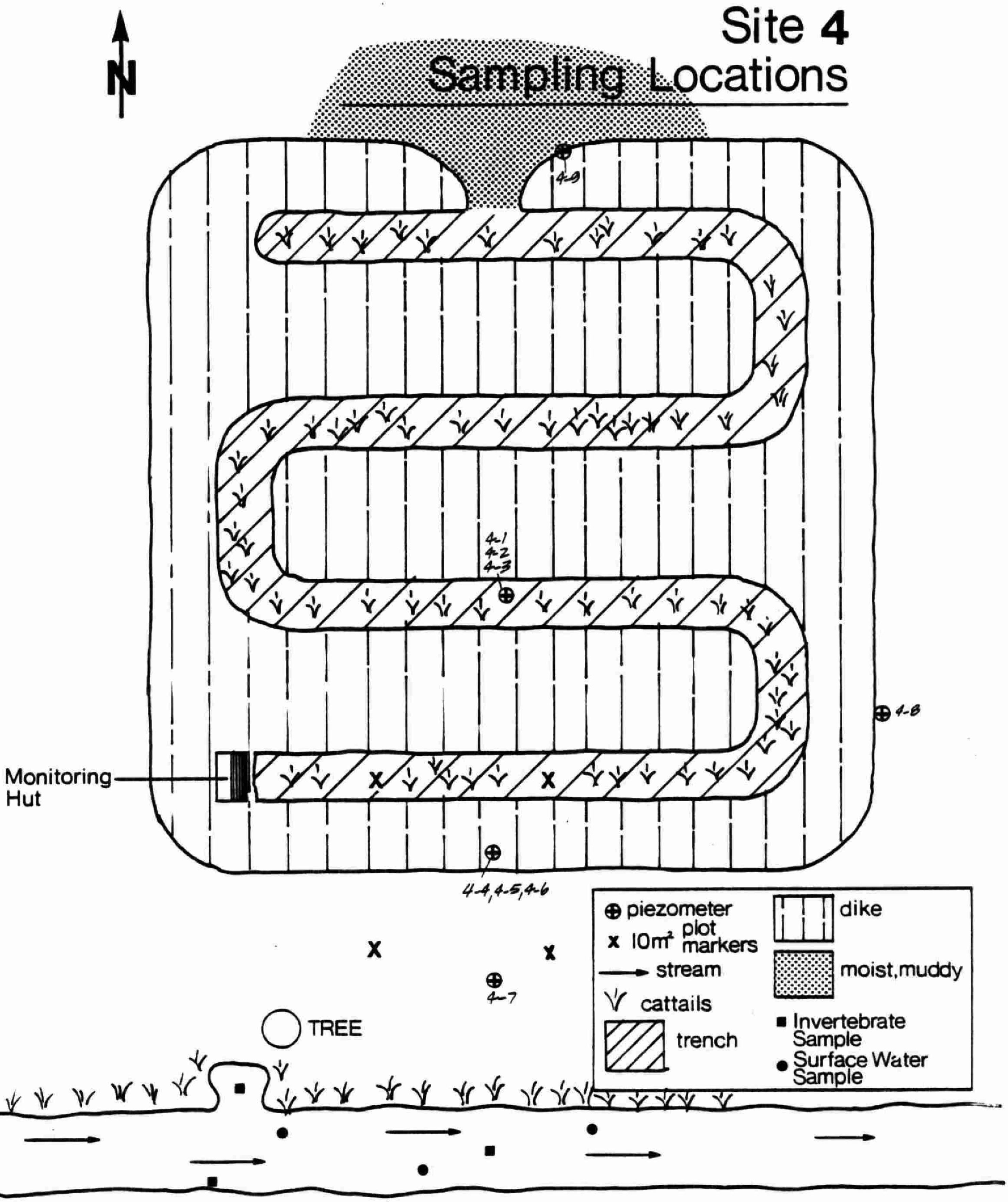
Site 3 Sampling Locations



SCALE 1:200

Fig. 5

Site 4 Sampling Locations



SCALE 1:400

Fig. 6

3.1.5 Decomposition Experiment

This experiment focussed on the rate of heavy metal release from decomposing vegetation. Concern has been expressed regarding the potential uptake by vegetation of heavy metals and their subsequent release during decomposition. This mechanism could potentially increase the mobility of contaminants in the environment.

To examine this mechanism, cattail stalks (*Typha latifolia*) were collected and placed in nylon mesh bags. Two sets of bags were submerged and secured at two sites. The first set were placed in the natural enriched marsh (Site 3) and the second in the artificial marsh (Site 4). A total of 12 bags were positioned at each site in mid-October. In addition, a sample of the vegetation was collected, dried and analyzed for heavy metals to act as a reference for comparison.

Single bags were collected from each site initially on a biweekly schedule. Mid-winter, the schedule was changed to one per month. The last bags were collected in mid July. The close initial spacing of samples was intended to provide insight as to rapid metal releases during the early stages of decomposition.

The bags at Site 4 were relocated on February 16, 1984 to the adjacent artificial marsh built on natural organic material. This was necessary since the artificial marsh on the tailings drained as a result of a washout of one of the berms and the bags were no longer submerged.

The digestion and analysis of the samples were performed using the procedure described in Section 3.2.2. The litter was washed and 3 replicate samples were sorted, dried, and weighed prior to digestion and analysis.

3.2 LABORATORY EXPERIMENTS

The laboratory experiments centered on the tailings cores that had been collected from each of the four study sites. The columns were leached with various solutions to see how metal release rates were affected. In analyzing the metals released, bioavailability was determined using a plant uptake monitoring procedure.

3.2.1 Apparatus Set Up

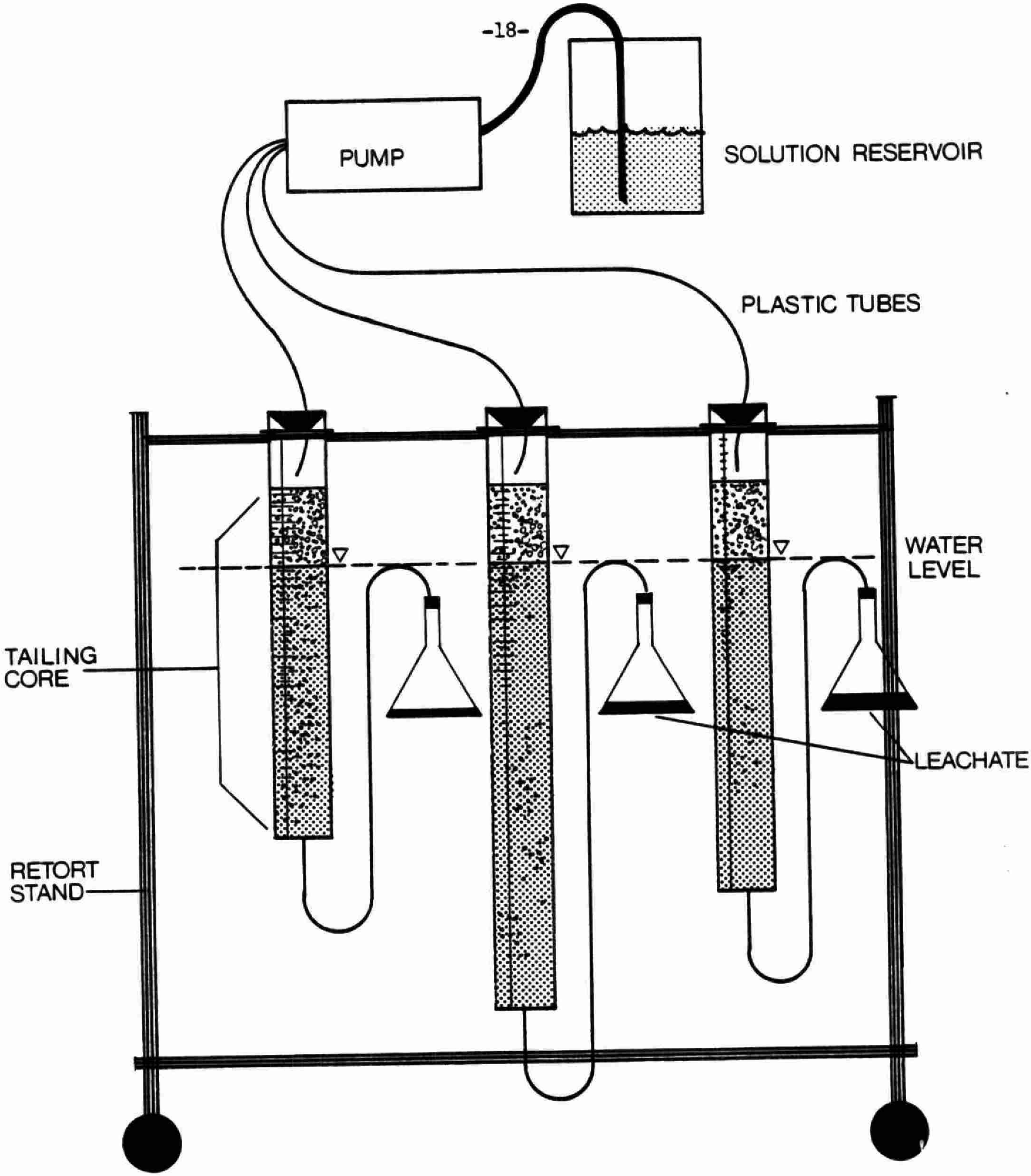
Intact cores of tailings were collected during the first field survey in mid-October. Plexiglass tubes, 6.4 cm in diameter, were manually forced into the tailings and then drawn out. The ends of the tubes were sealed with duct tape and the cores were stored in a upright position.

In the laboratory, plexiglass plates with spigots were glued to the base of each column and the cores were then mounted on a retort rack with the upper surface of tailings at the same level in each (Figure 7). Tygon tubing was used to conduct the leaching solution to the top of the columns and the leachate from the columns to sealed flasks. Plates of plexiglass with holes drilled to the diameter of the tubing were placed on top of the columns to minimize evaporation and contamination.

A common reservoir held the leaching solution which was pumped to the columns with a peristaltic pump.

3.2.2 Leaching Solutions

A series of leaching solutions and conditions were used to assess the mobility and bioavailability of heavy metals in the cores. They were selected to represent the types of changes that are anticipated if an artificial marsh sewage treatment system were to be built on the tailings. Specifically, two solutions were used, i) neutral, dilute, unenriched water and ii) neutral, higher conductivity, nutrient-enriched water. The dilute solution was designed to represent the natural leaching process (eg, rain). The other solution is typical of sewage effluent in Cobalt (G. Miller, pers.comm.). The characteristics of the two solutions are shown in Table 2.



LEACHING EXPERIMENTS—SETUP OF APPARATUS

Fig. 7

Table 2 Chemical Characteristics of Leaching Solutions

	Dilute Unenriched	Higher Strength Enriched
pH	6.0	6.8
Conductivity (uohms/cm)	4.5	350-400
Total Phosphorus (mg/l)	<.01	1.5
Nitrate (mg/l)	<.01	0.86
Ammonia (mg/l)	<.01	3.45

Three conditions were combined with the leaching solutions, namely i) watertable below surface (ie, 20 cm), ii) watertable above surface (ie, 2 cm) and aerobic, and iii) watertable above surface and anaerobic.

The anaerobic condition was simulated by using a layer of vegetable oil on top of the water surface to prevent oxygen exchange.

Combining the two leaching solutions and three leaching conditions resulted in six treatments in total.

Each column was dosed with solution until four or five leachate fractions of about 100-150 ml each had been collected. Each treatment took between two and four weeks for all fractions to be obtained. The daily hydraulic loading to the cores varied according to the rate at which the solution passed through the column. There was considerable variation among columns with Column #2 having a particularly low permeability. The average daily dose was in the order of 40 ml.

The treatments were ordered such that the expected most severe conditions were applied last. The order of the treatments was as follows.

Residual water
Dilute, watertable below surface (Treatment 1)
Dilute, watertable above surface, aerobic (Treatment 2)
Enriched, watertable below surface (Treatment 3)
Enriched, watertable above surface, aerobic (Treatment 4)
Dilute, watertable above surface, anaerobic (Treatment 5)
Enriched, watertable above surface, anaerobic (Treatment 6).

After each treatment, the cores were not drained and each followed on continuously.

When the columns were collected, pore water was retained in the tubes. As a result, the first series of samples collected were in fact not a result of the treatment being applied but were rather the discharge of the residual waters. To deal with this lag, a final leaching solution was used after the six treatments consisting of high concentration chloride (conductivity >3,000 uohms/cm). Samples were collected acidified and submitted for analysis from each column until the chloride solution appeared. At this point the leaching was terminated for the column. Based on the volume of the fractions collected between the end of the last treatment and the appearance of the chloride solution, the leachates samples were matched to the treatments by shifting the results by the appropriate lag for each column.

3.2.3 Bioavailability

A primary concern with the leachate samples collected was the proportion of heavy metals in solution that was biologically available for uptake by plants and animals. An uptake monitoring procedure was used to provide an estimate of bioavailability.

Each leachate fraction was separated into two parts. One was used as a growth medium for duckweed (*Lemna minor*) and the other was submitted directly for analysis. The part used to test bioavailability was supplemented (eg, 1 ml/100 ml leachate) by a stock solution of nutrients required for growth by duckweed. Then approximately 100 plants were placed in 250 ml plastic beakers. Controls were grown in distilled water supplemented by growth medium. The beakers containing the duckweed were placed in growth chambers and grown under controlled light and temperature conditions for seven days.

All plants in each beaker were then harvested, rinsed with distilled water, dried and weighed. The dried samples were digested for 48 hours in a heated nitric acid solution. On completion of the digestion, the samples were filtered and submitted for heavy metal analysis.

3.2.4 Data Analysis

All samples were analyzed using an Inductively Coupled Plasma Analyzer, Model Number 3400 manufactured by Applied Research Laboratories. The detection limits and precision of the instrument are shown in Table 3.

Standard (certified value) reference materials of appropriate matrix (water, sediment, plant material) subjected to the same fixation or digestion procedures were run at the same time as the samples.

Table 3 Detection Limits and Precision of ICP Analyser

	Detection Limit (ppb)	Precision (± ppb)
Arsenic	22	5
Copper	2	5
Nickel	14	5
Zinc	4	5

For all samples submitted for elemental analysis, results were reported for 22 elements. However, a number of elements were identified as being of particular significance and the concentrations of most of the other elements were closely correlated. As a result, it was decided to focus attention on a subset of elements consisting of arsenic, copper, zinc, and nickel. The results of this report deal specifically with these elements although results are available for most other heavy metals.

The results presented have been corrected in all cases by subtracting the concentrations of the elements measured in blanks and controls for each analysis.

4.0 RESULTS OF FIELD STUDIES

This chapter presents the results of the sampling program for the four monitoring plots. The results are presented in terms of soils, hydrology, chemistry and biology. Secondly, the litter decomposition experiment results are reviewed.

4.1 MONITORING PLOTS RESULTS

4.1.1 Description of Plots

Four plots were selected to represent the factors listed in Section 1.3.

Site 1, the unenriched undisturbed site, is located between Cart and Peterson Lakes immediately west of Ragged Chute Road. The tailings basin was operated by Teck Corp. and the mining operation was closed in the spring of 1983. The watertable is near or at the surface and the vegetation community is a meadow marsh. The site does not receive any municipal sewage effluent and is therefore unenriched with nutrients.

Site 2, the dry unenriched plot, is within the lease area of Sulpetro and much of the area is currently being reworked to recover residual silver in the tailings. During the monitoring period, a ditch was dug through the center of the plot. This has had a significant effect on the groundwater flow. The area is generally dry with a sparse tolerant vegetation cover. This site is also unenriched.

Site 3 is located immediately adjacent to Site 2 and is located at the confluence of a sewer outfall from the Town and the stream draining the area east of the railway tracks. The watertable is at or above the ground surface and the plot is dominated by cattail. This site represents the enriched, natural marsh condition.

Site 4 is northeast of the arena and encompasses the experimental artificial marsh sewage treatment system constructed on mine tailings. In February of 1984, one of the berms failed and the marsh drained dry. Sewage was no longer pumped into the system. Accordingly, the results from this site are not fully representative of the disturbed enriched conditions, but no alternative site was available.

4.1.2 Soils

The tailings at each site varied somewhat in terms of particle size, organic content and depth. Mineralogical variations are captured in observed variations in groundwater chemistry and the leaching experiments.

4.1.2.1 Site 1 (Undisturbed, unenriched).

Much of the tailings at Site 1 has apparently originated from a temporary discharge point established at the north end of the tailings basin. A fan-shaped beach of tailings developed outward from the road, spilling into the existing marsh. Testing with an auger indicated that tailings had not reached into the alder and bullrush community on the eastern side of the marsh near the road culvert.

The depth of tailings at Site 1 was found to be approximately 1 m. A 0.10 m layer of peat was encountered beneath the tailings. This peat developed on soft silty fine sand and clayey silts that were penetrated to a depth of 3 m by augering (Figure A-1).

The total organics in the tailings determined by loss on ignition are quite variable (Table 4). The second stratum is mixed with peat and has a high organic content (ie, 50%). Overall the organic content is moderate compared to the other sites.

The grain size of these tailings is predominantly in the fine sand and silt range (see Appendix A, Figures A-2 to A-6). The columns from this site were the most impermeable of those collected. The low permeability is also reflected in the pumping test results.

4.1.2.2 Site 2 (Dry, unenriched).

The tailings at Site 2 are older than those at Site 1 and originated from a mill that had been located to the southwest of the plot. They extend to a depth of 2.5 to 3 m based on the excavated profile along the drainage ditch. The organic content of these tailings is quite low (ie, less than 2%).

The material falls primarily in the range of medium sand (Figures A-8 to A-10) with high hydraulic conductivities (Figure A-7).

TABLE 4 PHYSICAL CHARACTER OF TAILINGS STRATA FROM EACH MONITORING SITE

Site Number	Sample Number	Texture	Loss on Ignition	Strata Length (cm)
1	3A	S Si	2.9	6
1	3B	S Si	50.2	13
1	3C	Si Cl	0.5	46
1	3D	S Si	0.5	19
1	3E	S Si	2.9	8
1	3F	Si	1.2	16
2	4A	c-m S	0.4	12
2	4B	c-m S	2.1	11
2	4C	m S	0.8	12
2	4D	c-m S	0.6	32
2	4E	c-m S	1.2	4
3	8A	m S	5.3	31
3	8B	S Si	2.3	17
4	10A	f-m S	0.2	45
4	10B	f-m S	0.9	11
4	10C	m S	8.4	28
4	10D	m S	.0	25

CODING:

c -coarse
f -fine
m -medium

Cl-clay
S -sand
Si-silt

4.1.2.3 Site 3 (Undisturbed, unenriched).

Site 3 consists of a mixture of tailings and recent organic deposits, most of which has originated from the sewage effluent. Tailings range in depth up to a maximum of about 2.5 m.

Particle size varies somewhat between strata but much of the material is in the fine sand and silt classes (Figures A-12 and A-13). Hydraulic conductivities reflect this pattern and are in the range of 2.5 to 8 x 10^{-4} cm/s (Figure A-11).

The organic content was on average high at this site (ie, 2-5%) compared to the others. Part of this material likely has an allochthonous origin given the sewage load to the site.

4.1.2.4 Site 4 (Disturbed, enriched).

The tailings used to construct the artificial marsh are the coarsest of those sampled and consist primarily of coarse to medium sand (Figures A-15 and A-16). They range in depth up to 3 m (Figure A-14). Their hydraulic conductivity was not measured but is estimated based on grain sizes to be in the range of 10^{-3} to 10^{-4} cm/s

The organic content of the tailings was low (ie, less than 1%) except immediately adjacent to the sewage channel where levels were elevated somewhat.

4.1.3 Surface Water Hydrology

All of the sites have a defined overland drainage channel flowing through or adjacent to them.

4.1.3.1 Site 1 (Undisturbed, unenriched).

Site 1 is located adjacent to Cart Lake which is a headwater lake and flows into Peterson Lake. There is little elevation difference (less than 0.2 m) between these two bodies. About 85 % of Cart Lake is filled with tailings.

The connecting stream is intermittent and flow is generally less than 1 l/min. A beaver dam extends for approximately 100 m across the outlet to Cart Lake; the site is situated below the dam. The ground surface is essentially flat and marshy.

4.1.3.2 Site 2 (Dry, unenriched).

Prior to the construction of the drainage ditch through Site 2, no overland drainage channels were present. All drainage was either through infiltration or surface sheet flow. The purpose of the drainage ditch is to conduct flow directly through the tailings in order to lower watertables and to permit access to the area through which the stream originally flowed. The dewatered tailings are being excavated and remilled.

The surface of the tailings is even and gently sloped (ie, <0.25 %) in a north northeasterly direction. The spoil banks from the ditch are piled along both sides of the channel creating an irregular ridge of bare exposed material.

4.1.3.3 Site 3 (Undisturbed, unenriched).

Site 3 encompasses the confluence of a sewer outfall stream and a natural stream. Each stream has an average flow of about 20-40 l/min. Adjacent to the two defined channels are standing pools of water which slowly exfiltrate through the marsh to the streams. The drop through the site is about .2 m and the water flow is fairly rapid in the channels.

4.1.3.4 Site 4 (Disturbed, enriched).

The artificial marsh at Site 4 had, at the beginning of the study, standing water originating from a discharge pipe conducting municipal sewage. At no point during the monitoring period did water flow through the outfall of the system but rather it exfiltrated through the porous berms. In mid-February a berm failed and no further sewage was pumped to the marsh. The primary stream carrying sewage and runoff runs parallel to the eastern boundary of the plot. The flow in this stream is about 100 l/min.

4.1.4 Groundwater Hydrology

Groundwater flow patterns generally follow that of the surface drainage system. Vertical gradients varied substantially but all systems appeared to be local in scale due to the impermeable silty clay soils and bedrock underlying the sites.

4.1.4.1 Site 1 (Undisturbed, enriched).

A nest of 4 piezometers plus 1 upstream piezometer was established at Site 1. Two of the piezometers in the nest were installed in the fine grained natural deposits underlying the tailings at depths of 3.4 and 1.8 m (P1-1 and P1-2). The other two were installed in the tailings at depths of 0.9 and 0.5 m (P1-3 and P1-4 respectively). The fifth piezometer (P1-5) was installed to a depth of 0.6 m in the tailings, 4 m upstream from the nest.

The direction of groundwater flow within this area follows that of the surface drainage and the horizontal gradients are low due to the relatively flat terrain (Figures A-17 to A-19). The hydraulic conductivity was found to be in the range of 10^{-5} to 10^{4} cm/sec reflecting the relatively fine-grained nature of the tailings.

The average depth of the water table below the surface at this site was 0.3 m (Figure A-20). Vertical gradients suggest minor downward movement in the upper strata but no major recharge or discharge systems are present.

A consistent pattern is apparent among the four sites monitored with a pronounced lowering of the standing levels and vertical gradients in the deepest piezometers. In all cases, the deepest piezometers were implanted in fine-grained tailings or native soils. The vertical gradient and standing level effects suggest that a temporary "perched" watertable forms within the coarser-grained tailings during the warm summer months. Following periods of rainfall, the tailings are saturated but the underlying silty clays are relatively impervious preventing the water from moving down through this layer. The poor hydraulic connection between these layers explains the temporal disparities between the vertical gradients within the same nest. The effect is most pronounced when a hot dry period, such as that experienced in early July, is followed by several days of wet weather like those immediately preceeding July 16 (Figure A-33).

4.1.4.2 Site 2 (Dry, unenriched).

Six piezometers were installed at Site 2. A central nest of three (P2-1, P2-2, P2-3) was installed to depths of 3, 2.5 and 0.8 m, plus three piezometers were installed to 2.5 m depths in a radial pattern away from the nest.

Piezometer P2-1, installed at a depth of 3 m, appears, based on the slow recovery rate, to be situated in natural silty materials beneath the tailings. All others are in the tailings proper.

In October 1983, a northward flow gradient was present (Figure A-21). After the drainage ditch was constructed, the groundwater flow pattern was altered substantially with the flow being directed toward the channel (Figures A-22 and A-23).

Vertical gradients at Site 2 tend to be weak near the surface and are much more pronounced deeper in the tailings (Figure A-24). In mid-July, downward gradients increased considerably. In mid-August, the gradient was steepest and this also corresponds to both a slightly dry period and a time when extensive tailings excavations were taking place nearby. The water table ranged between 0.5 m and 1 m below the ground surface and averaged 0.8 m over the period of observation.

4.1.4.3 Site 3 (Undisturbed, enriched).

A nest of three piezometers at depths of 2.67, 1.5 and 0.8 m (P3-1, P3-2, P3-3) plus two additional piezometers were installed to 1 m. The water level in the piezometers varied from 0.05 to 0.25 m below surface except P3-1 where the level was 1.5 m below surface two days after installation. This slow recovery rate suggests the piezometer tip is installed in silts or clays beneath the tailings.

The hydraulic conductivity of the tailings at Site 3 measured in piezometers P3-2, P3-3 and P3-4 varied from 2.5 to 8 10^{-4} cm/sec. Horizontal flow gradients follow the stream pattern (Figures A-25 to A-27).

Vertical gradients at this site followed those of Sites 1 and 2 (Figure A-28) although a more pronounced effect is apparent than at Site 2. On average, the watertable was about .3 m below the ground surface.

4.1.4.4 Site 4 (Disturbed, enriched).

Nine piezometers were installed at Site 4, including two nests of three piezometers. Nest 1 (P4-1, P4-2, P4-3) was located in the middle of the lagoon beside one of the channels. The maximum depth of penetration by driving was 1.2 m. The refusal encountered may be related to compaction that occurred during construction of the marsh. The second nest of three piezometers (P4-4, P4-5, P4-6) was installed at the toe of the lagoon embankment. The deepest in this nest

(P4-4) was easily driven to a 3 m depth. Three other downstream piezometers were installed around the lagoon at depths of 0.8 to 1.5 m.

At the time of installation, water levels in nest 1 were below the level of the sewage channel by 0.1 to 0.2 m showing a strong downward gradient. At nest 2, the water levels in the shallow piezometers were at ground surface: water seepage was observed at the embankment toe. The water level in the 3 m deep piezometer was 0.1 m below surface.

All the piezometers readily produced water and recovered rapidly. Although no hydraulic conductivity tests were carried out at this site they are estimated to be in the range of 0.5 to 1.0 10^{-3} cm/sec.

The horizontal flow changed after the discharge of sewage was stopped (Figures A-29 to A-31). In general, water levels dropped, and the gradients were less but the overall flow pattern remained much the same in terms of direction.

The pattern of vertical gradients at Site 4 was unusual in that a weak inverse relationship appeared to exist between the shallow and deep gradients (Figure A-32). In general, the differences in water levels between the piezometers were small and these gradient variations may be due simply to measurement errors. No strong upward or downward flows are apparent.

Standing levels at Site 4 followed the general trend of Sites 1, 2 and 3 with an overall lowering as the summer progressed.

4.1.5 Surface Water Chemistry

Considerable variation among sites in terms of surface water quality is evident. Much of the variation is due to the presence or absence of sewage effluent.

The surface water quality at Site 2 is reflected by that at Site 3 and the water passing through does not influence the chemistry or biology of the dry site. As a result, the water quality of Site 2 is not discussed further in terms of site ecology.

4.1.5.1 Site 1 (Undisturbed, unenriched).

Site 1 exhibited the most dilute surface water conditions of all. It had the lowest pH and conductivity (Figure A-34) and for most heavy metals had low concentrations (Figure A-35), the exception being arsenic; concentrations at Site 1 were similar to those at Site 3.

Surface water samples were collected from the slow moving stream through the site and from several adjacent pools. Table 5 presents values for select water quality parameters. The dilute, unenriched nature of Site 1 is seen by the low conductivity, total phosphorus, and pH. The concentrations of all other elements are similar to those for the other sites.

Table 5 SURFACE WATER QUALITY: SELECT PARAMETERS

Site Number	Alkalinity (mg/l)	Phosphorus Reactive (mg/l)	Total nitrogen (mg/l)	pH	Conductivity
1	131.2	.07	.4	6.2	290
2	120.4	.11	.6	6.8	440
3m	118.8	.12	.7	6.3	450
3s	373.2	<.02	6.2	6.8	460
4	94.2	.25	NA	6.7	350

4.1.5.2 Site 3 (Undisturbed, enriched).

The samples from the third site were segregated into moving and stagnant waters as there were consistent differences between the two. The samples from Site 2 provide some insight into the effect of discharging groundwater from the tailings on surface water quality since this is the only additional water inflow between Sites 3 and 2. The conductivity between the stations remains constant; however, pH increases downstream. Arsenic also increases downstream suggesting substantial leaching from the tailings. This may be partially due to recent disturbances. No major variations are seen among the other elements, although Site 2 tends to have higher concentrations of all elements when compared to the moving water at Site 3.

4.1.5.3 Site 4 (Disturbed, enriched).

Due to the failure of the berm at Site 4, no surface water was available for sampling within the plot. The results for Site 4 are from the adjacent stream and reflect generally the quality of the water which was being discharged into the experimental marsh. The primary difference from the other sites is the low concentration of arsenic. This variation may be due to leaching of arsenic from the tailings at other sites. The stream at Site 4 does not come into contact as extensively with tailings as do the other channels.

4.1.6 Groundwater Chemistry

Variations in groundwater chemistry are considered in terms of the influence of depth, differences between sites and antecedent weather and watertable conditions. Variations caused by depth are examined for each site individually. Variations between sites are seen by comparing the water quality of piezometers installed at the same depth in the tailings at different locations.

4.1.6.1 Metal Concentrations Among Sites

The results for piezometers at 0.9 and 1.5 m were compared. In Figure A-36, each piezometer represents one of the four sites. In the upper graph, all piezometers are at 0.9 m below the surface whereas in the lower one, they are at 1.5 m.

The relative ranking of all sites in terms of metal concentrations does not change between the two depths except for Site 1 which drops from having the highest levels at the 0.9 m depth to having the second lowest levels at 1.5 m. This shift is likely a result of the shallow depth of the tailings at Site 1. At 1.5 m, the piezometer (P1-2) is deeply embedded in native soils. The relative concentration of nickel however remains high at both depths at Site 1.

The ranking of sites with respect to the concentrations of heavy metals in groundwater was as follows:

Concentration: Rank	Highest 1	2	3	Lowest 4
Depth 0.9 m	1	2	4	3
1.5 m	2	4	1	3

The variability among sites is quite large and in the case of arsenic is as much as an order of magnitude. The variations are likely due to the characteristics of the ore and the milling processes and the history of the site since deposition of tailings.

4.1.6.2 Effect of Depth on Contaminant Concentrations

Few parameters showed a consistent trend with depth at all sites (Figures A-37 to A-44). The most striking observation was the high degree of variability within and between sites in terms of metal concentrations. Order of magnitude change were observed for arsenic within Sites 1 and 4. Nickel also tended to vary greatly within Sites 2 and 3 in particular. Copper and zinc concentrations were relatively consistent between all sites and at all depths.

Weak relationships with depth were apparent only for nickel. Nickel concentrations tended to increase with depth.

This high degree of variation suggests that chemical composition of the tailings is highly heterogenous. This heterogeneity should be considered throughout this report in attempting to interpret the results and even more so in the management of tailings themselves.

4.1.6.3 Effect of Watertable on Contaminant Concentrations

Two sets of samples were collected to observe the effects of watertable and antecedent weather conditions. The first set was taken after six days of hot dry weather; whereas the other was taken following several days of wet cool weather.

Heavy metal concentrations for the four sites are presented in Figure A-45. The unenriched sites, 1 and 2, tend to have slightly elevated arsenic concentrations under high water conditions. The enriched sites, 3 and 4, show little effect.

The differences between the wet and dry conditions were calculated and the difference was expressed as a percentage of the metal concentration under the wet conditions (Figure A-46). No element responded consistently among all sites. There was a tendency, however, for the largest percent increases to be positive (ie, an increase in concentration with wet conditions) suggesting that metal mobilization increases with increasing soil moisture. Zinc appeared to not follow this pattern and tended to be slightly less soluble under wet conditions. (Note: In both graphs, the upper limit of the "Y" scale is fixed and actual maximum percentage differences for Sites 1 and 2 were in the range of 600-800 %).

These results are not conclusive but do suggest that elevations in watertable lead to increased heavy metal concentrations in groundwater particularly in unenriched situations.

4.1.7 Vegetation

Vegetation varies considerably among the sites. Nutrient supply appears to account for most of the differences. The enriched moist site had the highest biomass density whereas the other sites had much lower densities. Metal burdens partly reflected this trend with the most productive sites having the lowest burdens and the least the highest.

4.1.7.1 Species Composition

Horsetail (Equisetum palustre) is the dominant plant species at Site 1 (undisturbed, unenriched) with an average canopy cover of 95 % (Table 6). It averages 549 stems/m^2 and 0.9 m in height. Interspersed throughout are individual stalks of cattail (Typha latifolia). Only four other plant species were recorded in the sample quadrats. There was an average total of 666 stems/m^2 for all species with 99 % canopy cover.

Dense clumps of bullrush (Scirpus validus), cattail and Canada bluejoint (Calamagrostis canadensis) were found scattered throughout Site 1. Close to the outlet, an open water cattail-alder (Alnus rugosa) marsh is predominant. The edges of the marsh are characterized by young stands of balsam poplar (Populus balsamifera) with red-osier dogwood (Cornus stolonifera), goldenrod (Solidago sp.) and reed canary grass (Phalaris arundinicae). Moving upstream from the plot towards the dam, horsetail becomes sparser and water levels increase.

Site 2 (dry, unenriched) is dominated by rush (Juncus filiformis) (805 stems/m^2) with occasional clumps of red osier dogwood (0.8 stems/m^2). Only 5 other species were recorded in the quadrat and species diversity at the site was low overall. Mosses were noted growing on the tailings at several locations. The overall average canopy cover was 79 % with 870 stems/m^2.

Cattails dominate Site 3 (undisturbed, enriched) accounting for 74 stems/m^2. Canada blue joint occurs as a subdominant (34 stems/m^2) around the margins of the cattail stands and in openings within the marsh. There was an overall average of 148 stems/m^2 and the vegetation cover was about 87 %.

Site 4 (disturbed, enriched) had the highest diversity due to the range in habitat types provided by the berms and sewage channels. Rush was the dominant species with 450 stems/m^2. Canada blue joint was a codominant and averaged 263 stems/m^2. The canopy cover averaged 124 %.

TABLE 6 SUMMARY OF VEGETATION SURVEY

	Site #	Equis. palustre	Typha latif. (living)	Typha latif. (seedling)	Lycopus unifl.	Calamagr. canad.	Typha latif. (dead)	Scirpus acutus	Eupator. macul.	Eupator. macul. (seedling)	Juncus filif.	Cornus stolonif.	Equis. prat.
#	1	548.8	3.2	0.0	23.2	87.2	0.8	2.4	0.4	0.0	0.0	0.0	0.0
%	1	95.3	0.9	0.0	1.8	1.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Ht	1	0.9	0.6	0.0	0.6	0.4	0.2	0.1	.0	0.0	0.0	0.0	0.0
#	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	804.8	0.8	64.0
% (live)	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.5	0.2	0.6
% (dead)	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.5	0.0	0.0
Ht	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	.0	0.3
#	3	0.0	28.8	44.8	0.0	34.4	0.0	0.0	0.0	0.0	0.0	0.0	35.2
%	3	0.0	51.5	0.5	0.0	13.1	6.5	0.0	0.0	0.0	0.0	0.0	15.1
Ht	3	0.0	1.8	.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2
#	4	4.8	0.0	0.0	2.0	262.8	0.0	0.0	88.8	31.2	450.4	0.0	60.0
%	4	0.2	0.0	0.0	0.2	31.0	0.0	0.0	0.6	0.3	19.5	0.0	10.5
Ht	4	.0	0.0	0.0	.0	0.4	0.0	0.0	.0	.0	0.6	0.0	0.1
Biomass	1	210.1	5.2	0.0	4.8	9.2	.0	.0	.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	223.0	.0	1.7
	3	0.0	679.4	0.3	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6
	4	.0	0.0	0.0	.0	33.0	0.0	0.0	.0	0.1	95.2	0.0	0.5

	Site #	Acer negundo	Acer rubrum	Solidago sp.	Glyc. striata	Bidens sp. seedling	Grass sp.	Grass (dead)	Viccia cracca	Moss sp.	Sphagh. sp.	Impat. capensis	Totals
#	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	666
%	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	99.25
Ht	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#	2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	870
% (live)	2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.3
% (dead)	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.5
Ht	3	.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
#	3	0.0	0.0	0.0	0.4	4.0	0.0	0.0	0.0	0.0	0.0	0.0	147.6
%	3	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	86.7
Ht	3	0.0	0.0	0.0	.0	.0	0.0	0.0	0.0	0.0	0.0	0.0	
#	4	0.0	0.0	0.0	0.0	0.0	144.8	0.0	0.4	0.0	0.0	3.6	1048.8
%	4	0.0	0.0	0.0	0.0	0.0	15.5	10.0	0.1	34.5	1.0	0.1	123.35
Ht	4	0.0	0.0	0.0	0.0	0.0	0.4	0.0	.0	0.0	0.0	.0	
Biomass	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	229.4
	2	.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	224.7
	3	0.0	0.0	0.0	.0	.0	0.0	0.0	0.0	0.0	0.0	0.0	680.8
	4	0.0	0.0	0.0	0.0	0.0	13.2	0.0	.0	0.0	0.0	.0	142.2

4.1.7.2 Biomass Density

Height-weight curves (Figure A-47) were derived for two major species, namely cattail and rush.

The equations used to estimate weight per stem were:

<u>Cattail</u>

if $H < .94$ m

$$W = 2.901 * H$$

if $H \geq .94$ m

$$W = 25.641 * (H - .83)$$

<u>Rush</u>

if $H < .32$ m

$$W = .1 * H$$

if $H \geq .32$ m

$$W = .5714 * (H - .21)$$

where H is the recorded height of the stems (m)

W is the estimated dry weight of the stems (g).

Biomass estimates (g/m^2) were derived by multiplying the number of stems/m^2 by the estimated weights per stem.

The highest standing biomass was recorded at Site 3 with 681 g dry wt/m^2. Site 1 and Site 2 had comparable biomass densities of 229 and 225 g dry wt/m^2 respectively. Site 4 had the lowest biomass density at 142 g dry wt/m^2.

The biomass density at Site 1 is low for a meadow marsh with densities usually in the range of 400-600 g drywt/m^2 (Gorham, 1974; Bernard and McDonald, 1974). This may partly reflect some inhibition of normal root development due to the presence of toxic contaminants. The densities at Site 3 are at the lower end of the normal range for cattail marshes (Odum, 1957; Jervis, 1969; Davis and van der Valk, 1983). The ready supply of nutrients likely partly accounts for the high productivity and the relatively low heavy metal concentrations in the tailings as compared to Site 1 (see Section 4.1.6.1).

4.1.7.3 Heavy Metal Burdens

Fresh vegetation samples were collected and analyzed from each of the 4 study sites. At Sites 1, 3, and 4, cattails were used and rush was sampled at Site 2 and 4. (Figure A-48).

Several relationships appear to exist.

i) Rush appears to concentrate heavy metals more than cattails. (Compare rush and cattail at site 4).

ii) Enrichment tends to increase metal uptake. (Compare cattail at sites 1, 3 and 4).

iii) Disturbance of tailings appears to increase the availability of heavy metals. (Compare rush at sites 2 and 4, and cattail at sites 1 and 4).

Overall the metal burdens for the four elements considered, namely arsenic, copper, nickel and zinc, are moderately high compared to other values reported. Table 7 presents the range of values for other sites and average values for each Cobalt site.

4.2 LITTER DECOMPOSITION EXPERIMENT

This section describes the results of the litter bag experiment. The experimental design is described in Section 3.1.5.

The original design was followed with one exception. As mentioned, a berm in the experimental marsh was breached in mid-February. As a result, the artificial marsh drained. The breach was not repaired and the marsh was not reflooded. It was necessary, therefore, to move the litter bags which remained in the marsh if the experiment was to continue. It was decided to place them in the experimental marsh built on native soils adjacent to the experimental system on tailings. The water entering both comes from the same source and the only difference between the two sites was the substrate.

The time of the switch over between sites occurred on February 13. A small increase in metal concentrations is apparent immediately following the move but no major prolonged effects are apparent that can be attributed to the change suggesting that the primary source of contaminants is the surface water.

TABLE 7 COMPARISON OF HEAVY METAL BURDENS IN VEGETATION FROM VARIOUS SITES

Location	Species	Contaminant Concentration (mg/g dry wt) As	Cu	Ni	Zn	Source
Cobalt: Site 1	T.latifolia	2.123	2.477	1.680	3.732	This study
Cobalt: Site 2	J.filiformis	1.708	1.350	<.002	21.155	This study
Cobalt: Site 3	T.latifolia	2.986	1.447	9.790	48.258	This study
Cobalt: Site 4	T.latifolia	4.462	2.371	2.498	9.572	This study
	J.filiformis	6.230	8.474	4.166	42.717	This study
Bancroft/Elliot Lake	P.tremuloides	-	.011	.006	-	Kalin, 1983
	Betula papyrifera	-	.01	.006	-	Kalin, 1983
England	Agrostis tenuis	1625*	-	-	-	Porter & Peterson, 1977
England	Agrostis tenuis	3470*	35	-	90	Porter & Peterson, 1975
Utah	Corn	-	21*	-	46*	Peterson & Nielson, 1973
Utah	Beans	-	80*	-	66*	Peterson & Nielson, 1973

* Indicates values are the maximum reported.

4.2.1 Variations Between Sites

The litter bags were placed in two locations, the natural (Site 3) and artificial (Site 4) marshes. The trends in metal concentrations between the two sites and the concentrations of contaminants were comparable (Figures A-49 and A-50). The temporal trends at each site were quite consistent.

4.2.2 Variations Over Time

The litter bags experiment was run from mid-November through to mid-July. The intention of the experiment was to determine the rate at which contaminants are released from decomposing vegetation. The results demonstrated, however, that decomposition lead to a concentration of heavy metals. The rate approximated the inverse of that typical for decomposition rates. Decomposition tends to decrease exponentially with time (Polunin, 1982). The reverse of this trend is reflected in total bound heavy metals (Figure A-51) and for each contaminant individually.

The trends for calcium and magnesium do not follow those for other metals and tend to decrease slowly with time (Figure A-52). In addition, total metal loads (ie, heavy metals plus calcium and magnesium) do not follow as clear a trend (Figure A-53). These observations suggest that heavy metals may be replacing calcium and magnesium as decomposition progresses.

The decomposition of plant cells results in a mass of free organic molecules being formed. As these molecules break down, exchange sites are formed and the heavy metals compete with hydrogen ions to form organic ligands (Bolter and Butz, 1976). This process leads to an increase in the number of sites for heavy metal attachment and a net increase in their concentration. This phenomenon is well known. Peat has been proposed on several occasions for polishing effluent and removing heavy metal contaminants.

The experiment does not answer the question of how long the trend of increasing heavy metal concentrations will persist. A longer period of investigation is necessary to answer this question definitively but estimates could be made by examining organic accumulation rates in wetlands and by taking cores of organic soils from Cobalt and measuring metal concentrations.

5.0 RESULTS OF LABORATORY EXPERIMENTS

This section presents the results of the experiments conducted with intact cores of tailings. The design of these experiments is outlined in Section 3.2. Their basic purpose is to determine under controlled conditions the influence that various environmental factors could have on the leaching rates and bioavailability of metals, in particular, nutrient enrichment, soil moisture status and anaerobic conditions.

5.1 LEACHING RATES

Table 8 summarizes the physical data for each column used in the experiment.

The metal concentrations in leachate from the columns were considered first in terms of differences among and within sites. Leachate concentrations were then examined among all columns in terms of the treatments applied.

5.1.1 Variations Between Sites

Each of the four sites was ranked based on the recorded metal concentrations in the groundwater (Section 4.1.6.1). Two columns represented each of the sites except for Site 4, the artificial marsh plot, for which there were three (ie, columns 11, 12 and 13). The metal concentrations in column leachate across all treatments were averaged for each site and plotted (Figure A-54). The ranking procedure was repeated and resulted in the following:

		Highest			Lowest
Rank		1	2	3	4
Element	As	2	4	1	3
	Cu	4	2	1,3	-
	Ni	4	2	3	1
	Zn	4	2	1	3

It can be seen that the relative ranks of the sites remained similar to that for the 1.5 m depth piezometers. This is expected since the columns from Site 1 were long and characteristic of the deeper strata. The results suggest that overall the columns were generally representative of the various sites and behaved comparably to intact tailings.

The high concentrations in the shallow groundwater of Site 1, the undisturbed unenriched plot, are not seen in the leachate from these columns. The columns from this site and, in particular, Column 2 had low permeabilities and it appears that the lower strata may consist of native soils and a natural organic layer. These layers appear to be intercepting part of the metals being leached from the upper strata.

5.1.2 Variations Among Columns from the same Site

The average metal concentrations in the leachate for the columns from Sites 1 and 4 (ie, columns 1 and 2, and 11, 12, and 13 respectively) are reasonably comparable within each site (Figure A-55). Both the absolute concentrations and the relative concentrations between metals remain similar within each, except for arsenic at Site 1 which varies substantially between Columns 1 and 2.

Conversely the columns from Sites 2 (ie, dry, unenriched) and 3 (ie, undisturbed, enriched), Columns 4 and 5, and 7 and 8 respectively, are quite dissimilar. In both cases, nickel generally is low in one column from each site and high in the other with the difference being an order of magnitude. Arsenic follows the same pattern as nickel for both sites. These observations reinforce those of the field sampling (see Section 4.1.6.2) which demonstrated the significant heterogeneity among and within sites.

The responses of columns from each site were examined relative to the various treatments (Figures A-56 to A-62). Some columns tended to show the same trends between each other, for example Columns 1 and 2, Columns 4 and 5, Columns 12 and 13. However Columns 7 and 8 and Column 11 were quite divergent in their chemical responses as compared to others from the same site.

A large number of explanations could be postulated for these differences between columns from the same site but no single explanation can be convincingly developed without further testing. Columns from the same sites appear to have similar characteristics; no single physical parameter appears to correlate to the observed differences. This high degree of variability draws attention to the complexity of the geochemistry of tailings and in particular, of predicting heavy metal mobilization.

5.1.3 Effects of Treatments

As discussed above, groups of the columns showed certain common trends but no consistent trend was apparent among all columns.

All columns except Columns 2 and 8, tended to have higher concentrations of one or more metals in the residual water than they did over most other treatments. These high metal levels in the residual water may be due to one or more of the following:

i) The columns were sealed and stored for approximately 4 weeks before the experiments could begin. Over this period, the residual pore water was able to reach equilibrium concentrations.

ii) It is expected that anaerobic conditions increased in the sealed tubes and redox potential dropped, increasing the mobility of the metals.

iii) Hydraulic loads to the columns were much higher (ie, 10 to 20 times) than natural infiltration rates which may have caused dilution over the course of the treatments.

The responses of one or more elements in most columns (eg, Column 4, 5, 7, 11, 12 and 13) followed a classic dilution mixing pattern. This would support the explanation that the high hydraulic loadings of the treatments may have caused an overall dilution of pore water. This response is weakest in the columns with the lowest permabilities further supporting this explanation. However, Column 8 has a moderately high leaching rate (Table 8) yet no dilution effect is evident. In many of the columns one or more elements appear not to follow the pattern (eg, arsenic in Columns 12 and 13). Why dilution would effect the various elements differently is not clear. Additionally, most metals tended to be at higher or similar concentrations in the leachate as compared to groundwater samples collected in the field.

The treatments were sequenced in the expected order of increasing severity with leaching rates expected to increase generally from Treatment 1 to Treatment 6. Some elements in some columns followed this trend, for example zinc in Columns 1, 2, 8, 11 and 13. Arsenic responded in a similar way in Columns 12 and 13. These two elements were the most responsive of the four to the treatments. The interesting question in these results is the absence of the overall expected trend in some columns and the high variability between columns.

TABLE 8 SUMMARY OF PHYSICAL DATA FOR LEACHING COLUMNS

Column Number	Site Number	Core Length (cm)	Number of Strata	DESCRIPTION OF STRATA # 1 A	B	# 2 A	B	# 3 A	B	# 4 A	B	# 5 A	B	# 6 A	B	# 7 A	B	Leaching Rate
1	1	103	4	18	mt	12	o+t	64	ft	11	o							S-M
2	1	120	5	18	mt	12	o+t	61	ft	11	o	18	fs					S
4	2	72	7	12	ct	12	dt	6	m+ft	18	ft	6	ct	12	ft	6	o+ft	M
5	2	80	7	12	ct	11	dct	12	m+ft	23	ft	6	ct	12	ft	4	o+ft	S
7	3	41	2	20	o+t	21	mt											S
8	3	48	2	31	o+t	17	mt											M
11	4	83	1	83	ct													F
12	4	86	1	86	ct													F
13	4	32	1	32	ct													F

CODING:

Column Headings		Texture	Composition	Colour	Leaching Rate
# 1	- indicates strata sequence in descending order starting at surface	c-coarse	o-organics	d-dark	F-fast
		f-fine	s-sand	l-light	M-moderate
		m-medium	t-tailings		S-slow
A	- Strata Length (cm)				
B	- physical characteristics of strata				

A number of columns showed a marked response to Treatments 4 (enriched, high watertable, aerobic) or 5 (unenriched, high watertable, anaerobic). This overlap between the two treatments may be due to the lack of a perfect plug flow through the columns. Treatment 5, the dilute solution combined with the anaerobic conditions was expected to increase leaching rates due to the higher solubility of some elements under these conditions (Bolter and Butz, 1973). Why this response only occurred in some columns and not others cannot be determined at this time.

To gain an insight as to the responses between sites, the results from the groups of columns have been combined. (Figures A-65 and A-66). These figures clearly show the dilution response for elements in a number of columns. Also the responses of arsenic and/or zinc to Treatment 4 or 5 is apparent to a lesser or greater extent at all sites.

If allowance is made for a dilution effect and the explanation for high residual water concentrations, the following responses to the treatments are apparent:

i) Mobilization rates of arsenic and zinc were most sensitive to the treatments used.

ii) Nickel concentrations varied significantly in some columns and tended to follow a dilution mixing pattern. The mobilization of this element was apparently not sensitive to the treatments used but was affected by the environment the residual water was subject.

iii) Arsenic concentrations generally decreased up to treatment 4 or 5 at which point a marked increase in concentration was noted.

iv) Zinc concentrations followed a dilution response pattern for the initial treatments and showed some increase in solubility with some of the "more severe" environments.

These combined results and the individual responses of the columns suggest that:

i) no simple relationship appears to exist between the physical and chemical environment of tailings and the mobilization rate of toxic elements;

ii) strong anaerobic conditions and/or long retention times tend to increase contaminant concentrations; and

iii) of the four elements considered in this study, their rates of mobilization in decreasing order are arsenic, zinc, nickel and copper.

5.2 BIOAVAILABILITY OF LEACHED CONTAMINANTS

A primary concern with contaminant mobilization is bioavailability. As described in Section 3.2.3, duckweed was grown in the leachate and contaminant burdens were then analyzed as a means to approximate available fractions.

Overall the trends in heavy metal concentrations appear similar across all treatments to the trends seen in metals in leachate samples. However, high rates of bioconcentration were noted.

5.2.1 Contaminant Burdens

The contaminant concentrations in the duckweed samples were measured on a dry weight basis (Figures A-67 to A-75). The concentrations of the contaminants in the duckweed correspond quite well in relative terms although the concentrations in the vegetation are one or two orders of magnitude higher. This general correspondence between the two types of measurements suggests that this technique to analyse bioavailable proportions of contaminants is reasonably reliable.

One methodological problem is apparent and that relates to whether the contaminants are simply adsorbed to the surface of the plants or are ingested and incorporated in the cell. The samples were thoroughly washed when they were harvested suggesting any adsorption must be quite secure.

Dead duckweed has been shown to bind greater quantities of contaminants than living specimens (Hutchinson, T.C. and H. Czyrska, 1975). In some of the cultures, the duckweed developed chlorosis although significant mortality was not noted.

To determine definitively whether the contaminants were bound in the cell structure or adsorbed to cell walls would require more elaborate analysis. While the matter of adsorption or ingestion is unclear, it does not appear that excess uptake due to dead cells likely was a factor. Furthermore whether the contaminant is adsorbed or ingested may not be significant since both forms are "mobile" within an ecosystem.

5.2.2 Effects of Leaching Treatments

The bioconcentration ratio is defined as the concentration of the element in the plant tissue divided by the concentration in the solution (Woolson, 1975). Figure A-76 illustrates the average bioconcentration ratios for duckweed for each of the treatments. The values range from about 100 to 2600 times the concentration in the leachate. These rates are in the range of those reported by Clark et al (1981) for duckweed for the metals considered.

The trends for the bioavailable fractions of arsenic and copper closely matched that of their concentrations in the leachate as a result their bioconcentration ratios are quite constant. Nickel was quite variable compared to copper and arsenic but no clear trend is apparent over the treatments. Zinc, however, tends to behave quite differently under the anaerobic conditions (ie, residual waters and Treatments 5 and 6). Overall, the bioavailability of this element appeared to increase with anaerobic conditions over the proportionate concentration in the leachate waters. It may be that this availability is due to different forms of the metal in solution which make it more readily available to duckweed.

Regardless of the specific mechanism, it appears that high watertable and anaerobic conditions tend to increase the bioavailability of zinc but not arsenic and copper and these conditions may cause some increase with nickel.

6.0 CONCLUSIONS

The following conclusions are based on the research described in this report in combination with the results available from other studies. The project has generated a substantial data base and these conclusions capture apparent major relationships. Undoubtedly, more extensive analysis of the results in terms of specific issues could yield further understanding.

In developing these conclusions, attention has been given to the primary objectives of the study, namely

i) future management prescriptions for tailings, in particular those in Cobalt, and
ii) design recommendations for the proposed artificial marsh sewage treatment system.

1) A high degree of variability is clearly apparent within and among the tailings sites studied. The variability relates to obvious physical features such as moisture and nutrient status, vegetation, physical texture and age of tailings. However, what appear visually to be the same materials taken from the same site may respond quite differently in terms of leachate concentrations.

   This variability demands that careful monitoring of any activities (be they tailings management or marsh construction) is undertaken in combination with normal analysis, prediction and design procedures.

2) Three factors were considered in this project, namely i) ionic strength and nutrient concentration, ii) soil moisture status, and iii) aerobic vs anaerobic environments, all had noticeable effects, either individually or collectively, on metal mobilization. Anaerobic conditions appeared to have the greatest effect followed by ionic strength of the leaching solution. Watertable conditions appear to have had the least effect.

   However, high leaching rates of contaminants occurred under all of the chemical and physical environments used in the treatments in one or more of the columns. Accordingly, contaminant leaching is a concern with the Cobalt tailings regardless of the chemical and physical environment, but, the greatest potential appears to exist with elevated watertables and strong anaerobic conditions.

3) Monitoring of the sites further demonstrated that higher watertable conditions tended to increase metal concentrations in groundwater. Arsenic, copper and zinc showed a positive increase with higher watertables; zinc appears to respond oppositely. None of these responses were consistent for all samples or sites supporting the fact that the geochemistry of tailings cannot be readily predicted.

4) The bioavailable fraction of the metals in the leachate were proportional to the concentration of the metals in solution. Those for arsenic, copper and nickel remained relatively constant over the treatments tested. Where an anaerobic environment existed zinc tended to become more available for uptake. This observation suggests that the form of some dissolved metals changes under these conditions.

5) Bioconcentration of metals in primary producers (ie, duckweed) was in the order of 100 to 2600 times that in solution. Many of the plants grown in the leachate solution showed toxic stress from the contaminant levels. Leaching of heavy metals from the tailings presents a significant toxic hazard to biological organisms.

6) Plant species, like duckweed, which tend to have high bioconcentration ratios will probably not be able to survive in the marsh system if elevated metal concentrations occur. The bioconcentration rates for cattail were much lower and the metal burdens did not appear to have a major inhibitory effect.

7) The risk of increased contaminant availability through uptake by marsh vegetation (eg, cattails) which might be caused by building a marsh treatment system in the tailings is offset somewhat by the apparent binding of metals by the decomposing vegetation. The net balance of metals could not be determined from the study results, but, a strong potential for binding is apparent.

8) The pH of the tailings is near neutral and no evidence of acid generation typical of pyrite-containing ore tailings is evident at Cobalt. Metal concentrations in the surface water and groundwater are high and significant leaching of metals appears to be occurring. Similarly high leaching rates were observed during the laboratory experiments with near neutral solutions.

9) Disturbance to the tailings is expected to increase leaching rates of contaminants. Due to the problems encountered with the experimental marsh system on the tailings (Site # 4), definitive conclusions cannot be reached, but tailings from this site yielded some of the highest concentrations of heavy metals in the leachate.

10) The primary concerns relating to increased metal leaching from the construction of a marsh treatment system are listed in order of importance:

   a) creation of strong anaerobic conditions
   b) development of elevated watertables, greater leachate quantities and more rapid groundwater velocities
   c) physical disruption to tailings and exposure of new material to leaching process
   d) supply of organic acids to adsorb metals
   e) increased biological uptake and availability through enhanced primary production.

7.0 RECOMMENDATIONS

These recommendations are set out in three categories, namely tailings management, marsh treatment system design and, lastly, areas requiring further research. The recommendations are based on the research undertaken on Cobalt tailings and this should be considered in interpreting and implementing these recommendations.

7.1 TAILINGS MANAGEMENT

These recommendations are intended to provide some guidance as to possible mitigative measures which could be used to deal with tailings contaminant management.

1) Efforts should be directed to maintaining as low watertable elevations as possible. Saturated soils tended to develop anaerobic conditions more readily than dry soils. Strong anaerobic conditions tend to lead to higher mobilization rates and higher bioavailable fractions.

2) Disturbance to tailings should be minimized since this may lead to higher leaching rates. The highest leachate consentrations were associated with disturbed tailings.

7.2 MARSH SEWAGE TREATMENT SYSTEM DESIGN

The recommendations pertaining to the marsh treatment systems are based on the concept that the facility might be constructed in a tailings deposit and design measures are required to minimize heavy metal leaching.

3) The marsh system should be designed to have shallow water depths to maximize oxygen exchange potential. Anaerobic conditions have been shown in other experimental marsh systems to cause a significant reduction in effluent treatment efficiencies and therefore shallow depths are generally used. In this case, strongly anaerobic conditions should be avoided as much as possible in the design to also minimize the potential for metal leaching.

4) The marsh channels should be excavated down to the low permeability native silty clay soils. These soils will reduce downward leaching rates and appear to attenuate contaminants. Suitable soils were encountered below the tailings at all of the sites investigated.

5) A litter management system needs to be devised for marsh vegetation. Decomposing litter appears to effectively adsorb dissolved heavy metals and is therefore valuable for effluent polishing. On the other hand, decomposition can lead to the production of organic acids and anaerobic conditions in groundwater. The challenge will be to optimize the adsorption rate against the potential for enhanced leaching.

6) A systematic monitoring system should be installed around the facility to gauge changes in leaching rates during operation. The results of this project highlight the great variability in the geochemical response of the tailings and therefore predictions of leaching rates have a high uncertainty which can only be reduced through actual sampling.

7) The system should be located on the downstream side of tailings deposition to minimize elevated watertable effects. If the marsh is located on the upstream side of a tailings deposit, consideration should be given to a groundwater collection system and/or a sealant for the channel walls.

7.3 FURTHER RESEARCH NEEDS

The axiom in research projects of this nature is that the answer to every question generates five new questions. This study is no exception other than the ratio may be closer to 10. The recommendations in this section are not intended to be comprehensive as a result, but are focussed on the major uncertainties facing managers dealing with tailings and activities associated with them.

8) There is a need to further define the key variables affecting leaching rates and explain the significant differences among tailings. This may be achieved to a certain extent by partitioning tailings cores by strata and comparing how each responds. By designing a linked system between the strata, leachate could be sampled as it passes from one strata to the other. In addition, combinations of strata could be artifically constructed and their joint performance determined.

9) The effects of disturbance to the tailings that will be necessary during construction should be quantified. An intention of this study was to address this matter but the difficulties with the artificial marsh system preclude definitive conclusions on the matter. The current extensive excavation operations of the Cobalt tailings for remilling offer an excellent opportunity to study this relationship.

10) The long-term dynamics of heavy metal accumulation in organic deposits needs to be examined. The litter bag experiment suggested that a net uptake of metals by decomposing organic material occurs but whether this is a short-term ephemeral mechanism or a long-term permanent sink is not clear. A survey consisting of sectioning cores from recent organic deposits on tailings could provide an indication of the duration and dynamics of this effect.

8.0 BIBLIOGRAPHY

Allen, H.E., and Unger, M.T. 1980. Evaluation of Potential Metal Mobilization from Aquatic Sediments by Complexing Agents. Z. Wasser. abw. Forsching. 13. p. 124-129.

Anastasi, F.B., and Kender, W.J. 1973. The Influence of Soil Arsenic on the Growth of Lowbush Blueberry. J. Environ. Quality. 2(3): 335-337.

Andrews, R.D. 1975. Tailings: Environmental Consequences and a Review of Control Strategies. In: T.C. Hutchinson (ed). Proc. First Int. Conf. on Heavy Metals in the Environment. Vol II part II: 645-675.

Bates, T.E., Haq, A., Soon, Y.K., and Moyer, J.R. 1975. Uptake of Metals from Sewage Sludge Amended Soils. Int. Conf. on Heavy Metals in the Env., Sym. Proc. Vol. II (Part 1), Toronto, pg. 403-432.

Bernard, J.M., and J.G. McDonald, Jr. 1974. Primary production and life history of Carex lacustris. Can. J. Bot. 52: 117-123.

Blair, R.D. et al. No date. Ground Water Monitoring and Contaminant Occurrence at an Abandoned Tailings Area, Elliot Lake, Ontario. Proceedings: First International Conference on Uranium Mine Waste Diposal. May 14-21. Vancouver. Society of Mining Engineers of Aime. Ed. by C.A. Brawner. Chapt. 29, pp 411-444.

Boissonneau, A.N. 1968. Glacial History of Northeastern Ontario. II-Timiskaming-Algoma Area. Map S465 Ontario Department of Lands and Forests.

Bolter, E., and Butz, T.R. 1976. Heavy Metal Mobilization by Natural Organic Acids. Proc. of the International Heavy Metals Conference 1975. Toronto, Canada. p. 353-362.

Buelow, D.I. 1983. Revegetating Precious Metal Tailings in Northern Ontario. Masters Thesis for University of Toronto. Dept. of Botany, Inst. of Env. Studies. Toronto. p 214.

Card, K.D., and S.B. Lumbers. 1975. Ontario Geological Survey Map 2361. Sudbury-Cobalt Geological Compilation Series. Ontario Ministry of Natural Resources.

Chapman, L.J., and M.K. Thomas. 1968. The Climate of Northern Ontario. Climatological Studies Number 6. Canada Department of Transport.

Chau, Y.K. 1973. Complexing Capacity of Natural Waters - Its Significance and Measurement. J. Chromatogv. Sci, 11, 573.

Cherry, J.A. et al. 1980. Surface Hydrology and Geochemical Evolution of Inactive Pyrite Tailings in Elliot Lake Uranium District, Canada. Proceedings: Third Symposium on Uranium Mill Tailings Management. Nov. 24-25, Fort Collins, Colorado. pp. 353-385.

Cherry, D.S., and Guthrie, R.K. 1979. The Uptake of Chemical Elements from Coal Ash and Settling Basin Effluent by Primary Producers II. The Science of the Total Environment 13: 27-31.

Clark, J.R., Vanhassel, J.H., Nicholson R.B., Cherry D.S., and Cairns J. Jr. 1981. Accumulation and Depuration of Metals by Duckweed. Ecotoxicology and Environmental Safety 5: 87-96.

Comanor, P.L., DeGuire, M.F., Hendrix, J.L., and Viceland, P. 1974. Effects of Previous Tailings Disposal on Upper Sonoran Vegetation of the Getchell Area. Trans. Soc. Eng. Amer. 256(3): 240-242.

Davis, G.B., and Van Der Valk. 1983. Uptake and Release of Nutrients by Living and Decomposing Typha glauca Godr. Tissues at Eagle Lake, Iowa. Aquatic Botany 16 75-89.

Dertz, F. 1973. The Enrichment of Heavy Metals in Submerged Plants. In: Advances in Water Pollution Research, ed. by S.H. Jenkins, 53-62. Oxford, Pergamon.

Down, C.G., and Stocks. J. 1978. Environmental Impact of Mining. Applied Science Publishers Ltd., London, England.

Environment Canada. Heavy Metals in Agricultural Lands Receiving Chemical Sewage Sludges. Research reports # 9, 25, 30, 51. Canada - Ontario Agreement on Great Lakes Water Quality.

Faust, S.D., and Clements, W.H. 1973. Investigation of the Arsenic Conditions at the Blue Marsh Lake Project Site Pennsylvania, U.S. Army Corps of Engineers Contract DACW 61-71-C-0288.

Fennstra, S.R. et al. 1981. Geochemical Investigations of Two Inactive Tailings Areas in the Elliot Lake Uranium District, Ontario, Canada. Proceedings: Fourth Symposium on Uranium Mill Tailings Management. pp. 367-388. Fort Collins, Colorado.

Gorham, E. 1974. The relationship between standing crop in sedge meadows and summer temperature. J. Ecol. 62: 487-491.

Guthrie, R.K., and Cherry, D.S. 1979. The Uptake of Chemical Elements from Coal Ash and Settling Basin Effluent by Primary Producers I. The Science of the Total Environment 12: 217-222.

Hahne, H.C.H., and Kroontie, W. 1973. Significance of pH and Chloride Concentration on Behavior of Heavy Metal Pollutants: Hg(11), Cd(II), Zn(11), Pb(11). J. Environment Qual. 2: 444-450.

Hawley, J.R. 1979. The Chemical Characteristic of Mineral Tailings in the Province of Ontario. Ministry of Environment. 234p.

Hiltbold, A.E. No date. Behavior of Organoarsenics in Plants and Soils. In Arsenical Pesticides. E.A. Woolson (ed). ACS Symp. Ser.7. pp. 53-69.

Hutchinson, T.C. and Czyrska, H. 1975. Heavy Metal Toxicity and Synergio to Floating Aquatic Weeds. Verk. Internat. Verein. Limbol. 19:2102-2111.

Jenne, E.A., and Luoma, S. 1978. Forms of Trace Elements in Soils, Sediments, and Associated Waters: An Overview of Their Determination and Availability. U.S. Geological Survey, Menlo Park, California.

Jennett, J.C., and Wixson B.G. 1975. The New Lead Belt. Aquatic Metal Pathways - Control. In: Int. Conf. on Heavy Metals in the Env., Sym. Proc. Vol. II (Part 1). Toronto. pg. 247-255.

Jervis, R.A. 1969. Primary Production in the Freshwater Marsh Ecosystem of Torey Meadows, New Jersey. Bull. Torrey bot. Club. 96: 209-231.

John, M.K. 1975. Transfer of Heavy Metals from Soils to Plants. In: Int. Conf. on Heavy Metals in the Env., Sym. Proc. Vol. II (Part 1), Toronto. pg. 365-377

John, M.K. 1974. Extractable and Plant Available Zinc in Horizons of Several Fraser River Alluvial Soils. Can. J. Soil Sci. 54: 125-132.

John, M.K. 1972. Influence of soil properties and extractable zinc on zinc availability. Soil Sci. 113: 222-227.

Kalin, M. 1983. Long-term Ecological Behavior of Abandoned Uranium Mill Tailings. 1. Synoptic Survey and Identification of Invading Biota. Technology Development Report EPS 4-ES-83-1.

Kalin, M. 1982. Long Term Ecological Behavior of Abandoned Uranium Mill Tailings: 1. Synoptic Survey and identification of invading Biota. EPS (Ottawa) Final Report. In press.

Kalin, M. 1981. Metal Uptake and Root Region pH in Typha latifolia on Uranium Mill Tailings.

Karbe, L., N. Antonacopoulos, and C. Schnier. 1975. The Influence of Water Quality on Accumulation of Heavy Metals in Aquatic Organisms. Verh. Internat. Verein. Limnol. 19 (1975) 2094-2101.

Khalid, R.A., R.P. Gambrell, and W.H. Patrick. Jr. Sorption and Release of Mercury by Missisippi River Sediment as Affected by pH and Redox Potential. Louisiana State, U.S. Baton Rouge, Louisiana.

Lane, D.P. and J.D. McDonald. 1979. Irrigation with Sewage Effluent on the Old Granby Tailings at Princeton, B.C. Proceedings: 3rd Annual British Columbia Mine Reclamation Symposium. Reclamation of Lands Disturbed by Mining. March 7-9, Vernon, B.C. Ministry of Mines and Petroleum Resources and Mining Association of B.C. Victoria.

Martens, D.C. 1968. Plant Availability of Extractable Boron, Copper, and Zinc as Related to Selected Soil Properties. Soil Sci. 106: 23-28.

McIlveen, W.D., and D. Balsillie. 1978. Preliminary Studies of Soils and Tailings in the Cobalt Area, 3rd Annual Meeting of the Canadian Land Reclamation Association, Sudbury, Ontario. My 29 (1978) 69-86.

Morel, F., R.E. McDuff, and J.J. Morgan. 1973. Interactions and Chemostatis in Aquatic Chemical Systems: Role of pH, pE, Solubility and Complexation in Trace Metals and Metal Organic Interaction in Natural Water, P.C. Singer (Ed.) pp. 157-200, Ann Arbor, Michigan.

National Research Council of Canada, Associate Committee on Scientific Criteria for Environmental Quality. Effects of Arsenic in the Canadian Environment. 1978. Publication No. 15391 of the Environmental Secretariat.

Odum, H.T. 1957. Trophic Structure and Productivity of Silver springs, Florida. Ecol. Monogr. 27: 55-112.

Okuhara, D. 1978. Effect of Surface Treatment of Tailings Areas on Quantity and Quality of Seepage. Part III. Rio Algom Ltd. Process Development Department Report No. R78-13. Elliot Lake.

Peters, T.H. 1978. Inco Metals Reclamation Program in Proc. Second Annual Meeting of the Canadian Land Reclamation Association. Laurentian University. May-June -78. ISSN-0705-5927.

Peterson, H.B., and R.F. Nielson. 1973. Toxicities and Deficiencies in Mine Tailings. In: R.J. Hutnik and G. Davis (Eds.). Ecology and Reclamation of Devastated Land, Vol.1: 15-25. Science Publishers Inc. New York.

Peterson, P.J. 1975. Element Accumulation by Plants and Their Tolerance of Toxic Mineral Soils. International Conference on Heavy Metals in the Environment, Symposium Proceedings Vol. II (Part 1), Toronto. pg 39-54.

Polunin, N.V.C. 1982. Processes in the Decay of Reed (Phragmites australis) Litter in Freshwater. In: Gopal, B. et al Wetlands: Ecology and Management. India. pp. 293-304

Porter, E.K., and P.J. Peterson. 1977. Arsenic Tolerance in Grasses Growing on Mine Wastes. Environ. Pollut. 14: 255-265.

Porter, E.K., and P.J. Peterson. 1975. Arsenic Accumulation by Plants on Mine Waste (U.K.). Sci. Total Environ. 4: 365-371.

Ray, S., and W. White. 1976. Selected Aquatic Plants as Indicator Species for Heavy Metal Pollution. J. Environ. Sci. Health, All (12), 717-725.

Reay, P.F. No date. The Accumulation of Arsenic from Arsenic-Rich Natural Waters by Aquatic Plants. pp. 557-565

Rodgers, J.H. Jr., D.S. Cherry., and R.K. Guthrie. 1978. Cycling of Elements in Duckweed (Lemna perpusilla) in an Ash Settling Basin and Swamp Drainage System, Water Research 12: 765-770.

Rowe, J.S. 1972. Forest Regions of Canada. Department of the Environment, Canadian Forestry Service, Ottawa, Ont. Publication No. 1300. 172 pp.

Whiteacre, R.W., and C.S. Pearse. 1974. Arsenic and the Environment. Colorado School of Mines Mineral Industries Bulletin 17(3): 1-19.

Woolson, E.A. 1975. Bioaccumulation of Arsenicals. Chap. 7. In: Arsenical Pesticides. Edited by E.A. Woolson. ACS Symp. Ser 7. pp. 97-107.

A P P E N D I X A

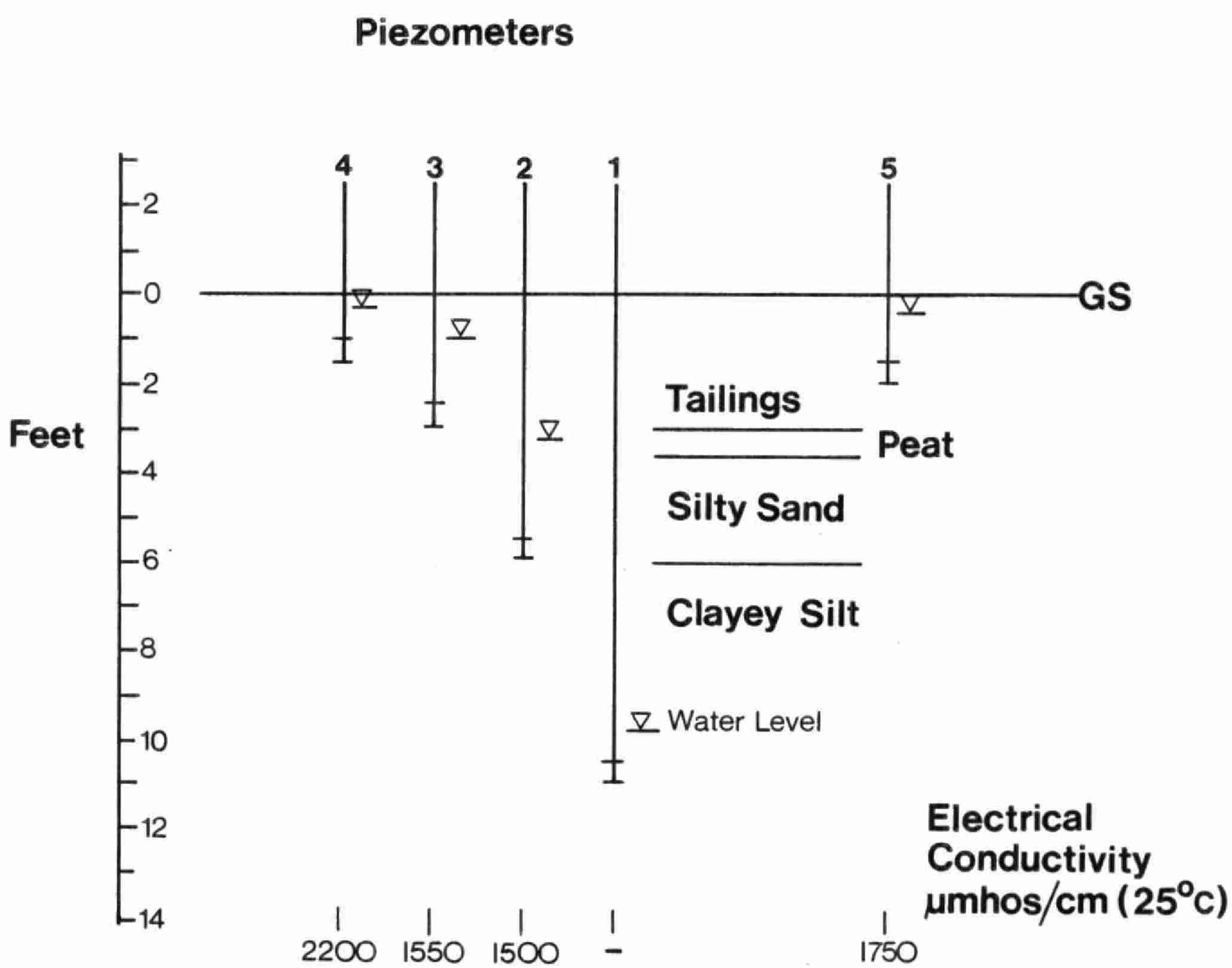
GRAPHS OF RESULTS

NOTE:

Figures A-2 to A-6, A-8 to A-10, A-12, A-13, A-15 and A-16 are derived from samples taken at each of the four monitoring plots. The sample station number codes refer to the location and strata of each and correspond to the codes used in Table 4, Section 4.1.2.

LIST OF FIGURES IN APPENDIX A

GROUNDWATER HYDROLOGY SITE 1
Oct.'83



HYDRAULIC CONDUCTIVITY

PIEZOMETER	cm/s
3	2×10^{-5}
4	1×10^{-4}
5	8×10^{-6}

NOTE: These groundwater levels were taken immediately following installation of piezometers and therefore do not represent stabilized levels.

HEAVY METAL MOBILIZATION AND BIOAVAILABILITY – COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

Tailings Sample Station Cobalt 3A

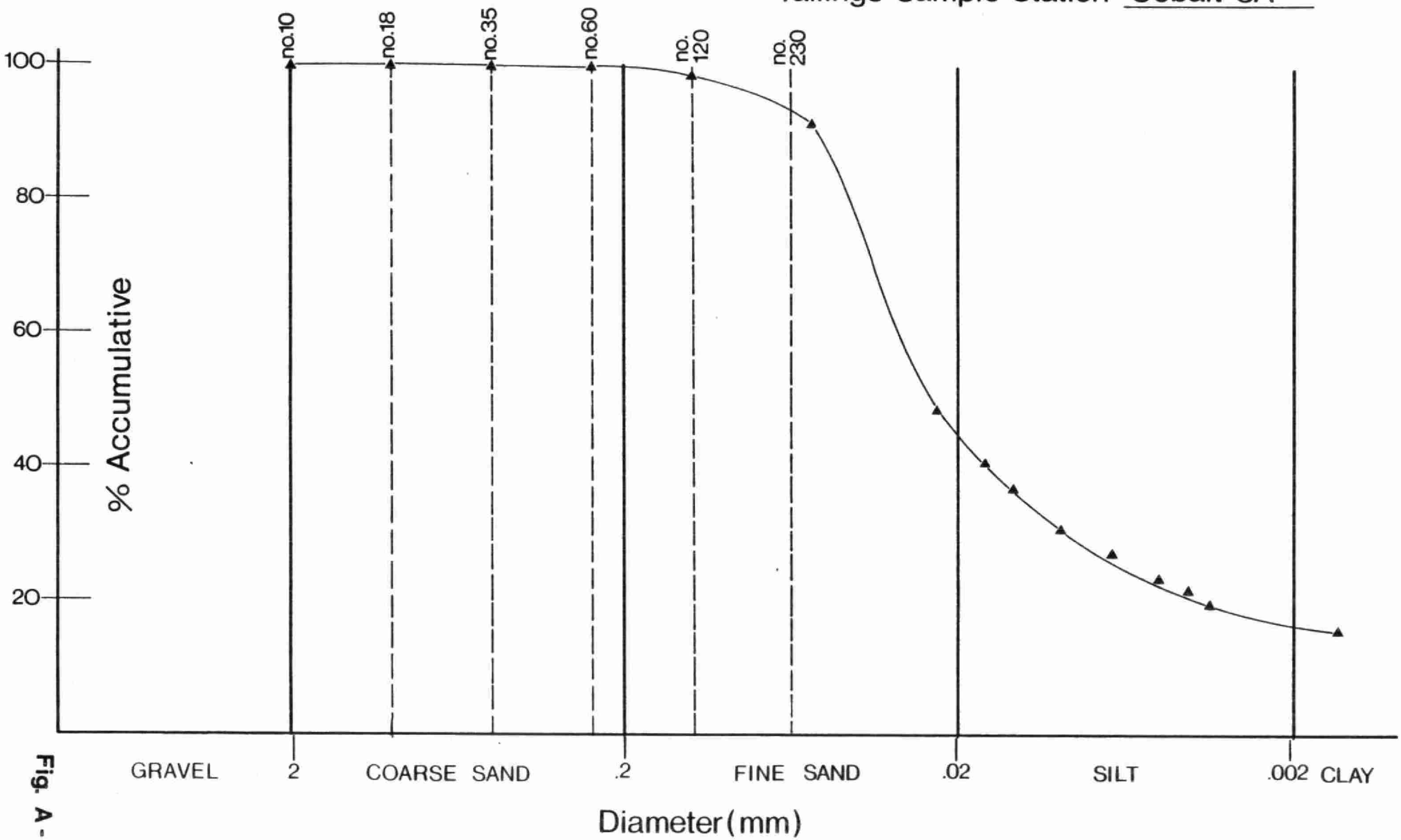


Fig. A - 2

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY -
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

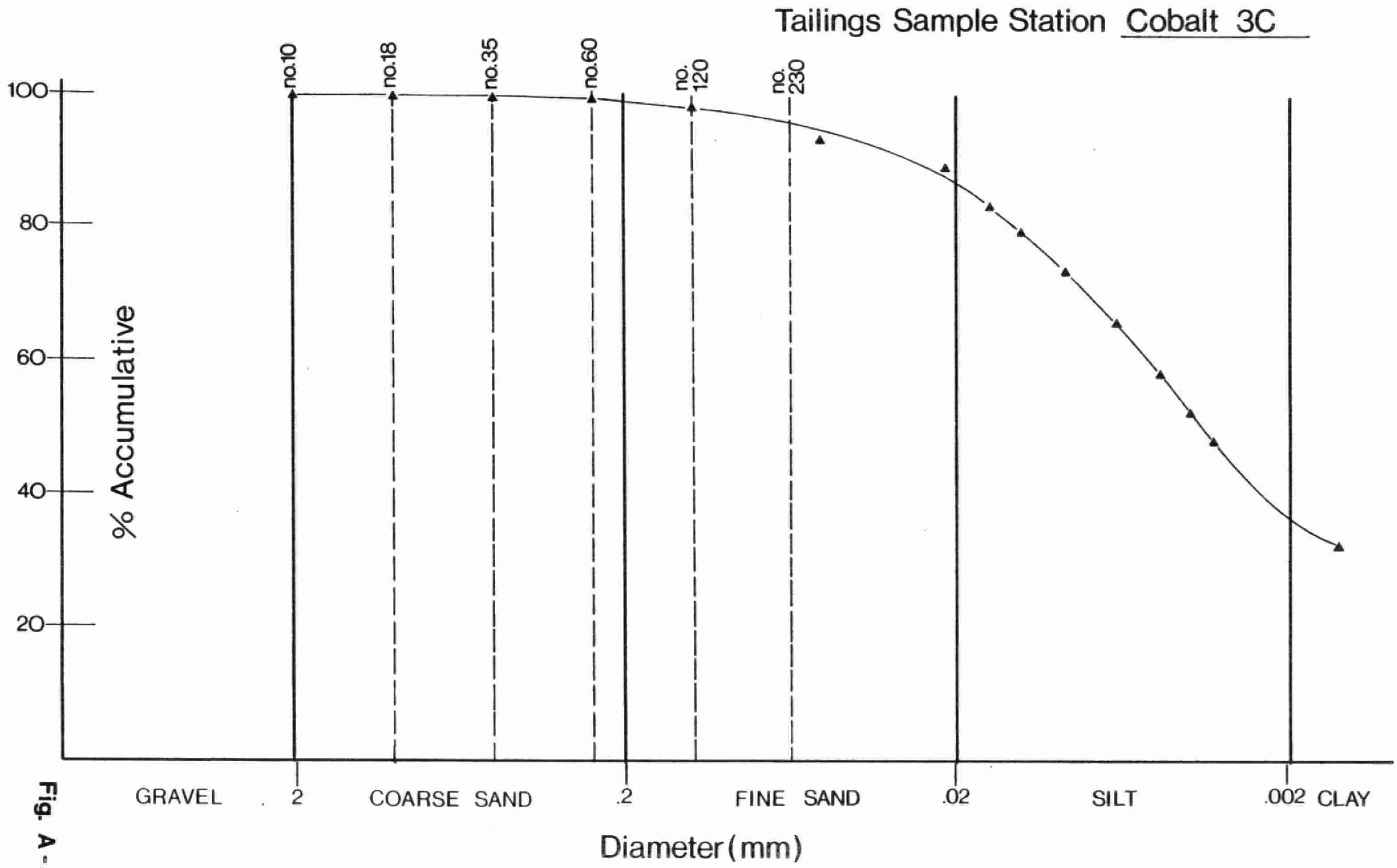


Fig. A-3

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

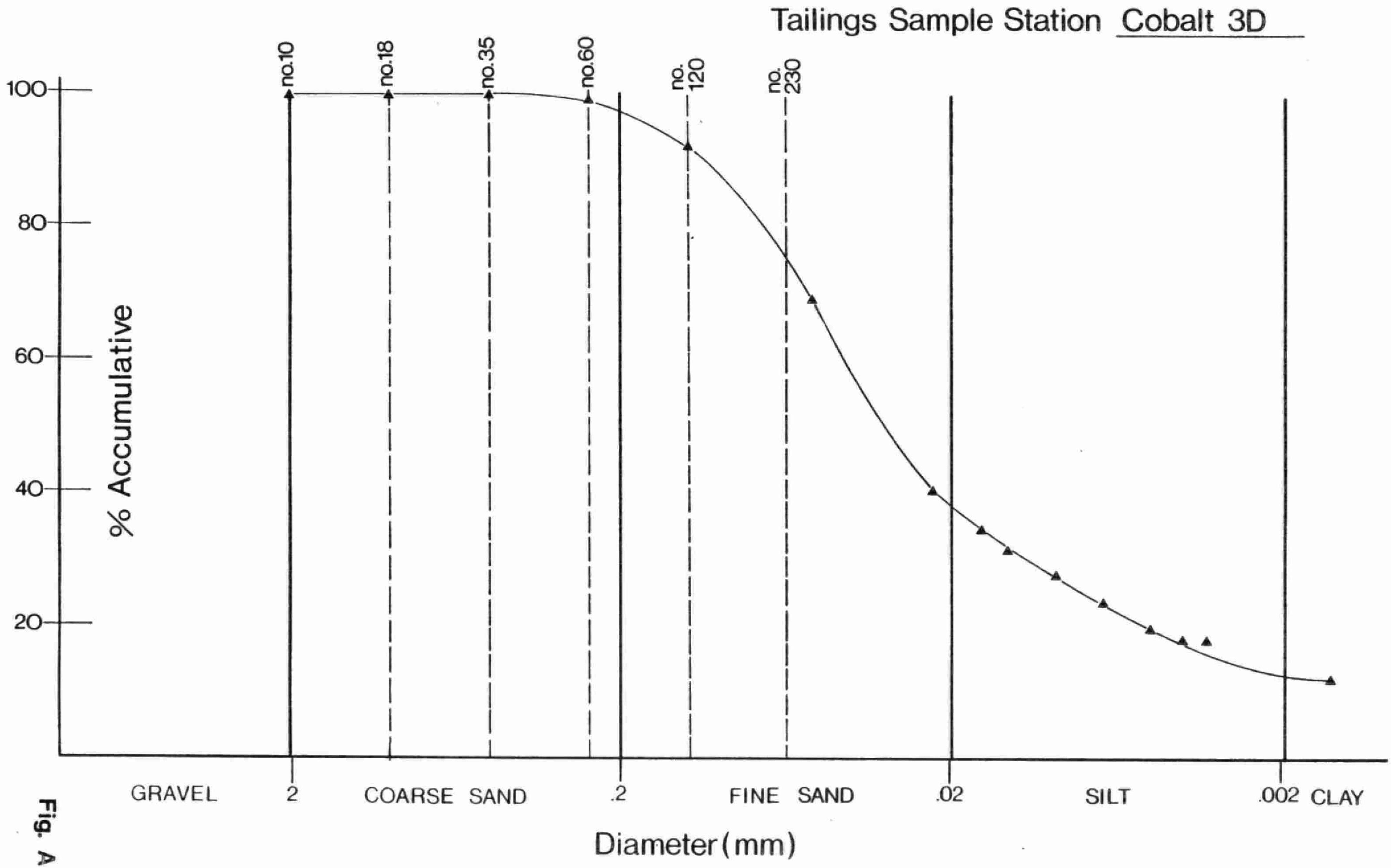


Fig. A - 4

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

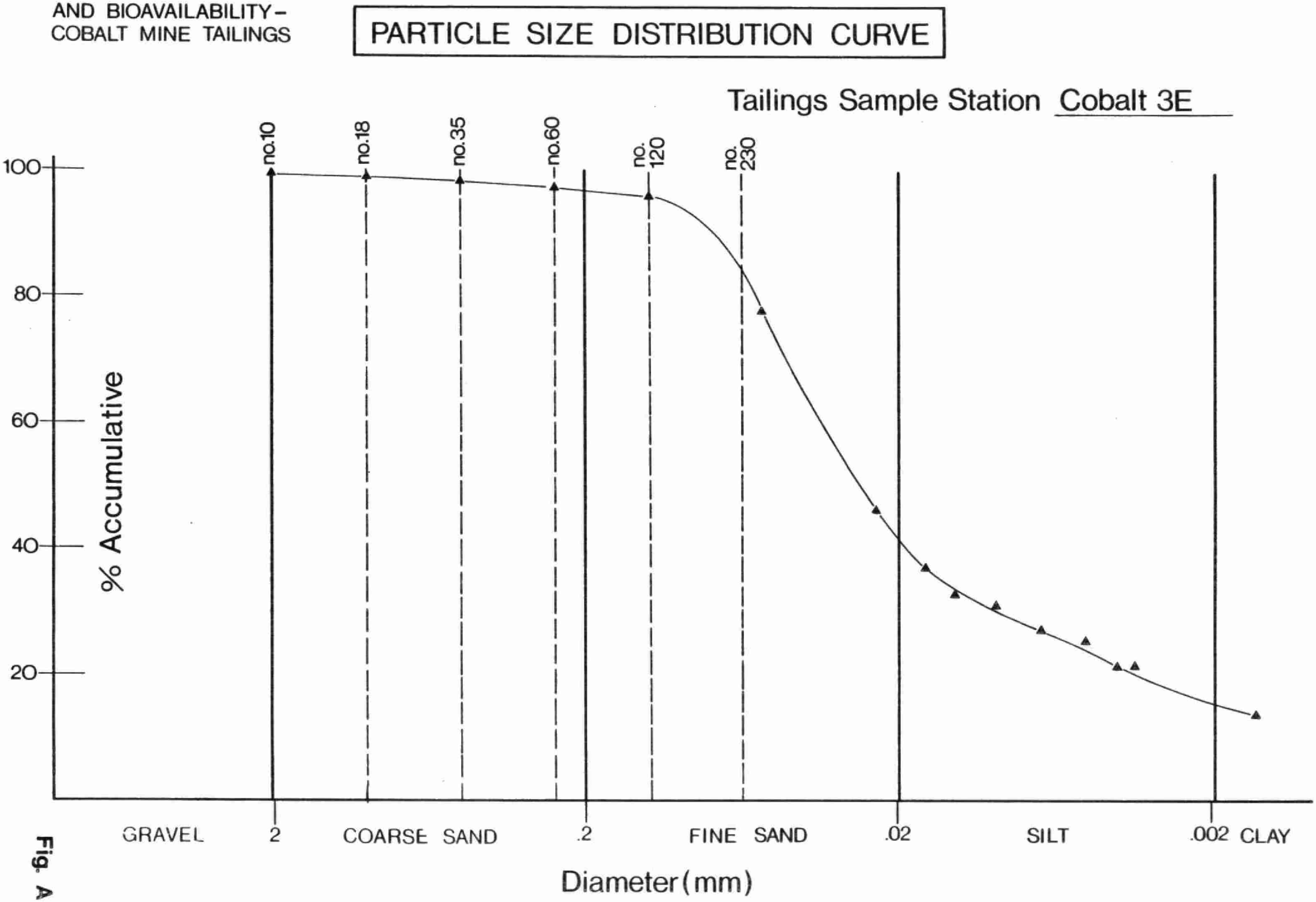


Fig. A - 5

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

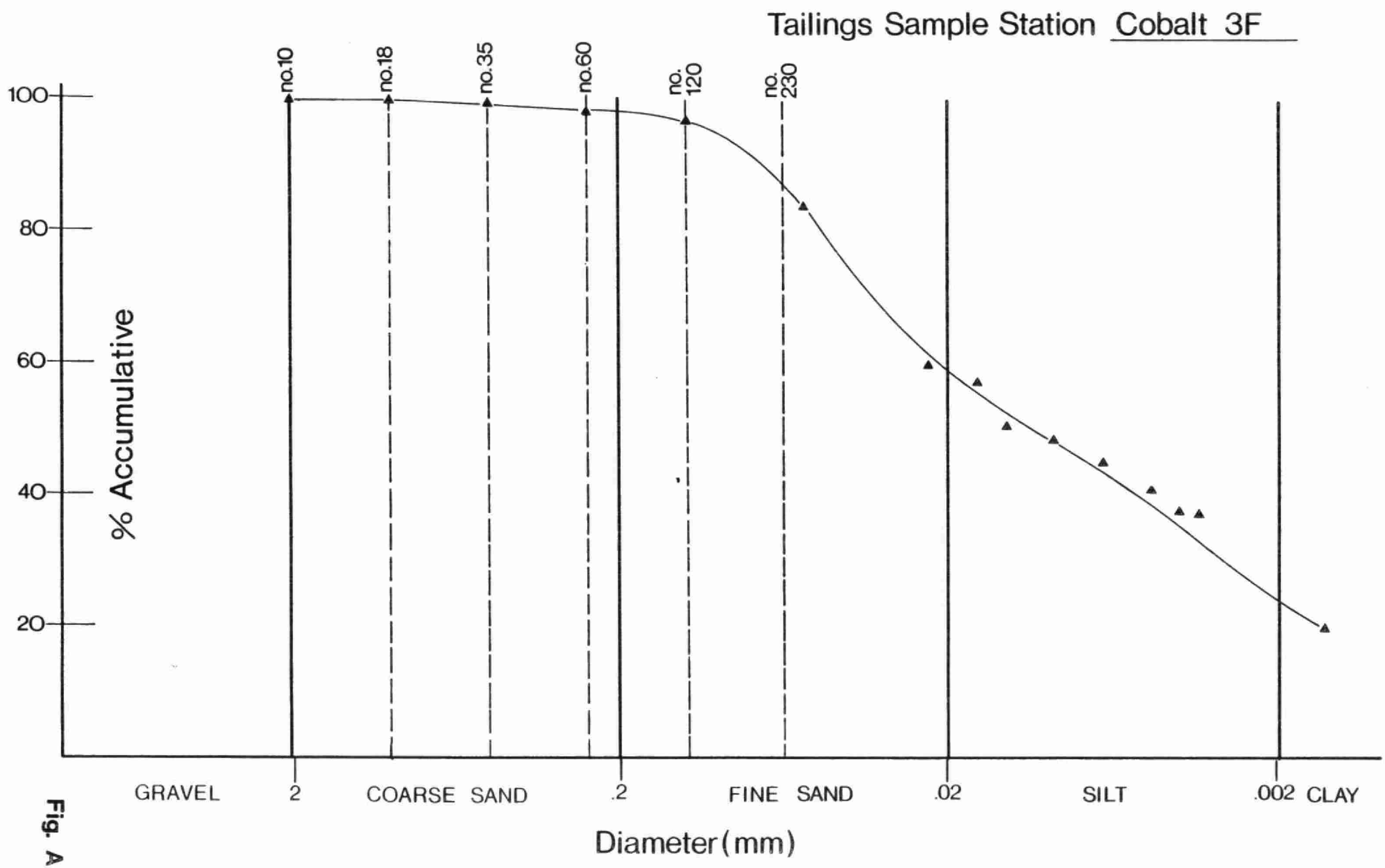
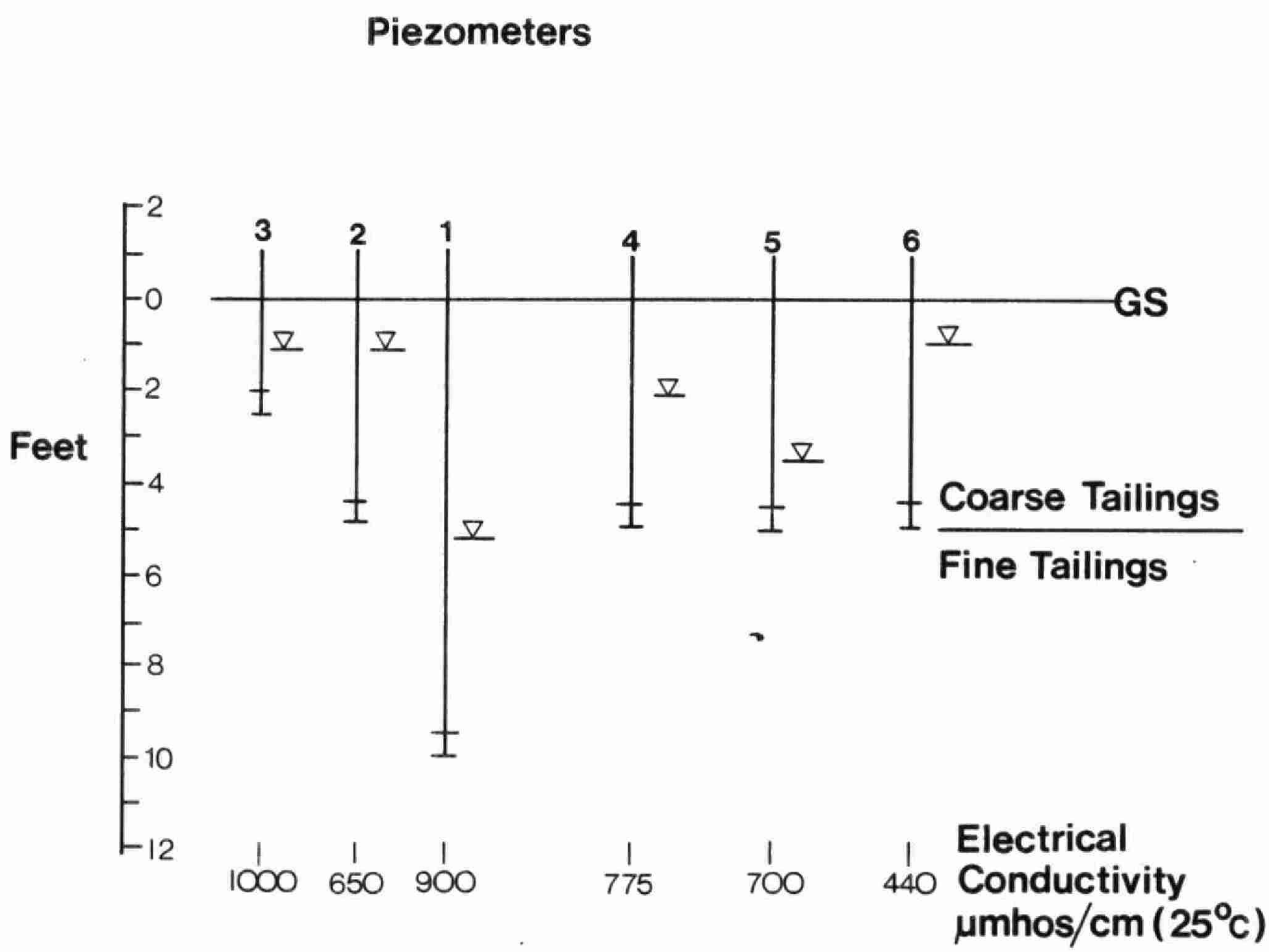


Fig. A - 6

GROUNDWATER HYDROLOGY SITE 2
Oct.'83



HYDRAULIC CONDUCTIVITY

PIEZOMETER	cm/s
2	5×10^{-4}
3	1×10^{-3}
4	7×10^{-4}
5	1×10^{-3}
6	2×10^{-3}

NOTE: These groundwater levels were taken immediately following installation of piezometers and therefore do not represent stabilized levels.

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

Tailings Sample Station Cobalt 4A+B

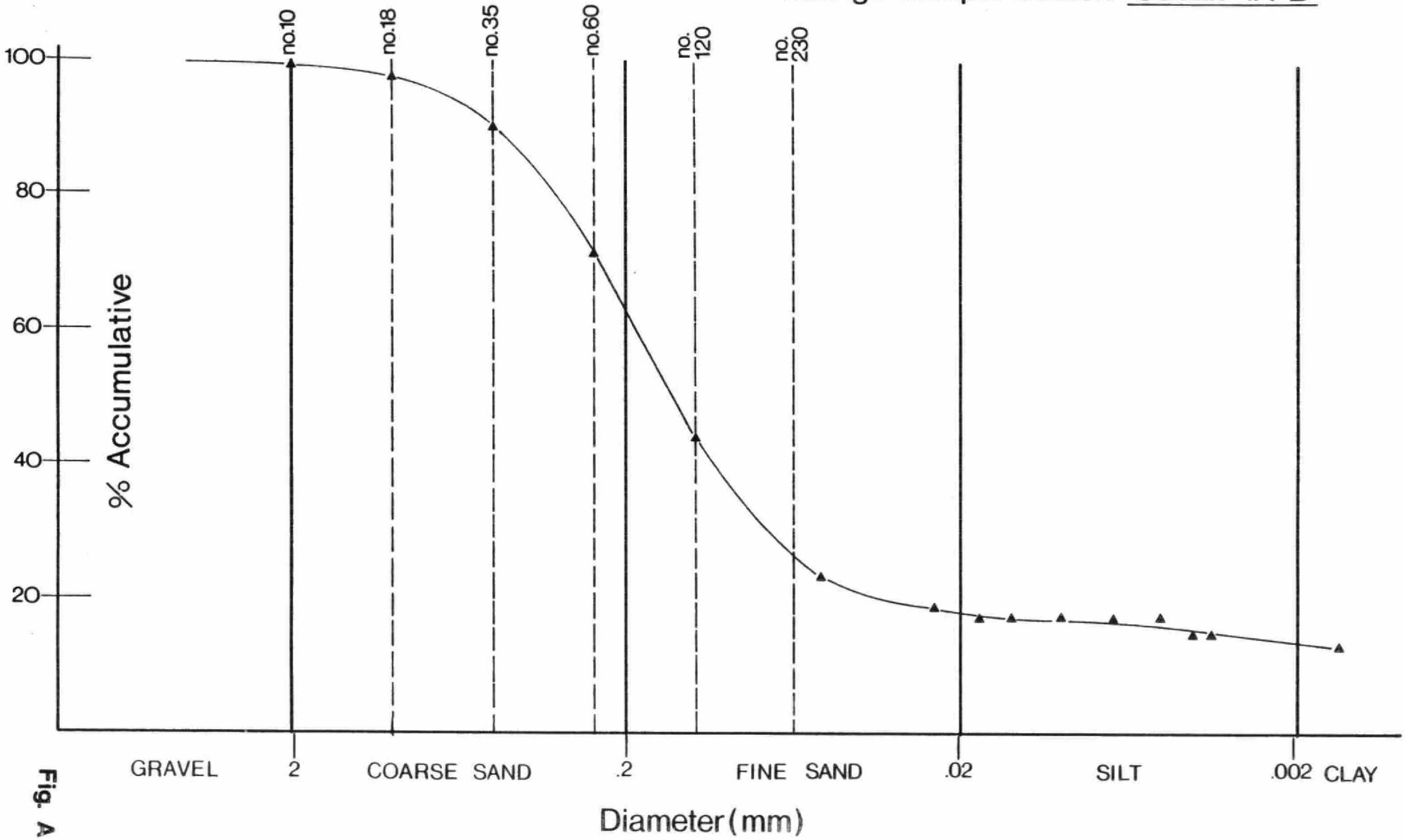


Fig. A - 8

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

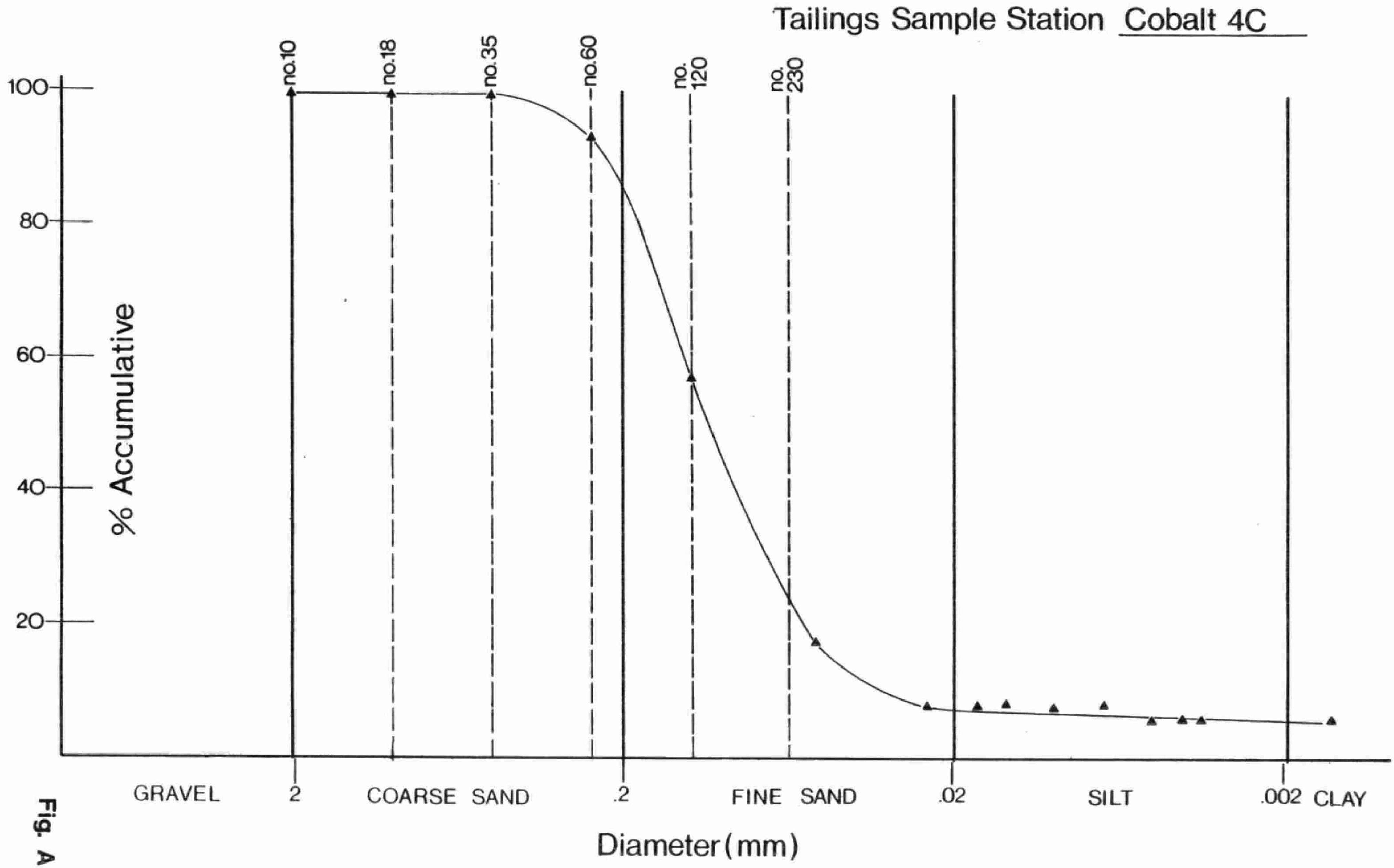


Fig. A - 9

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

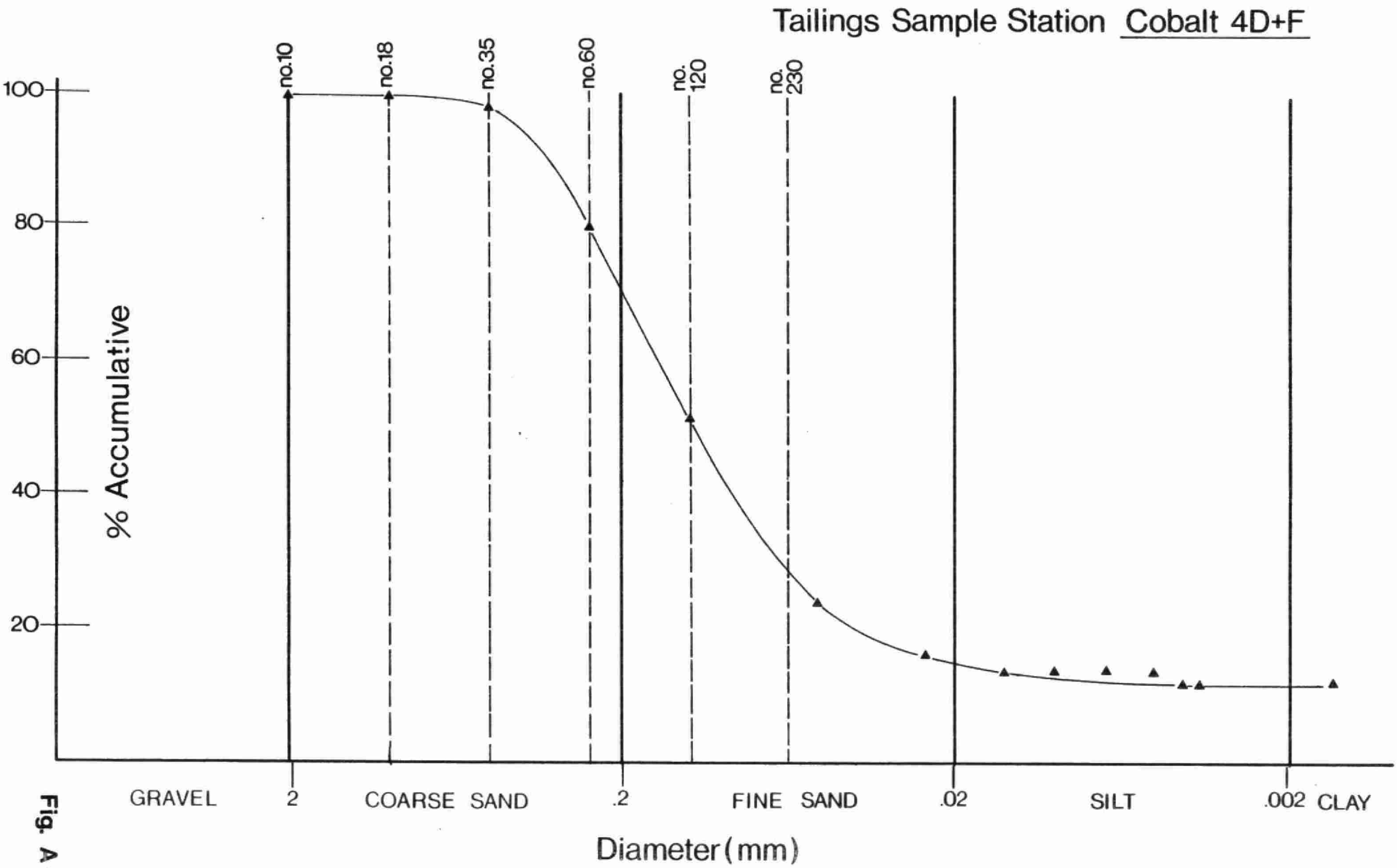
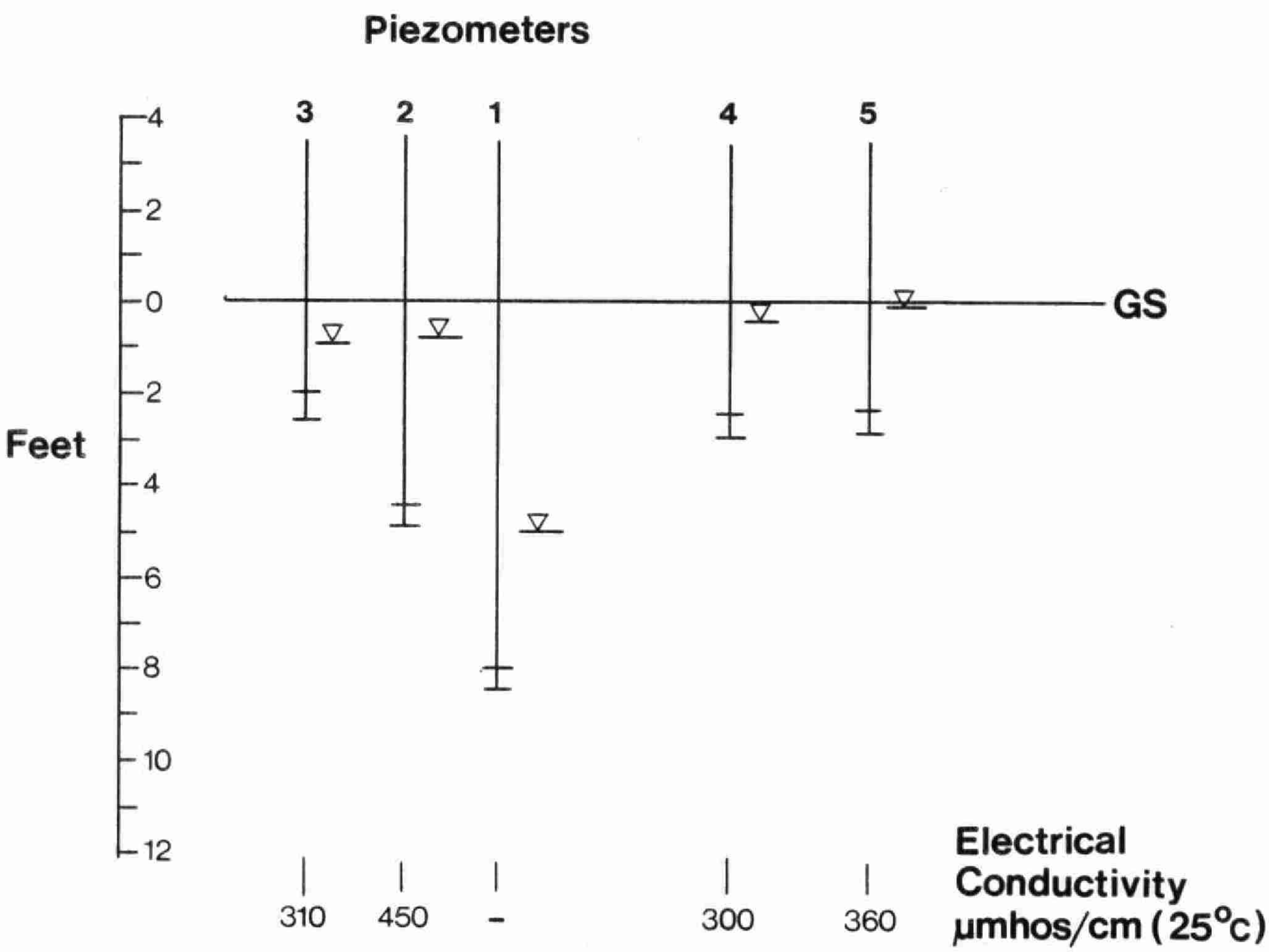


Fig. A - 10

GROUNDWATER HYDROLOGY SITE 3
Oct. '83



HYDRAULIC CONDUCTIVITY

PIEZOMETER	cm/s
2	2×10^{-4}
3	4×10^{-4}
4	8×10^{-4}

NOTE: These groundwater levels were taken immediately following installation of piezometers and therefore do not represent stabilized levels.

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

Tailings Sample Station Cobalt 8A

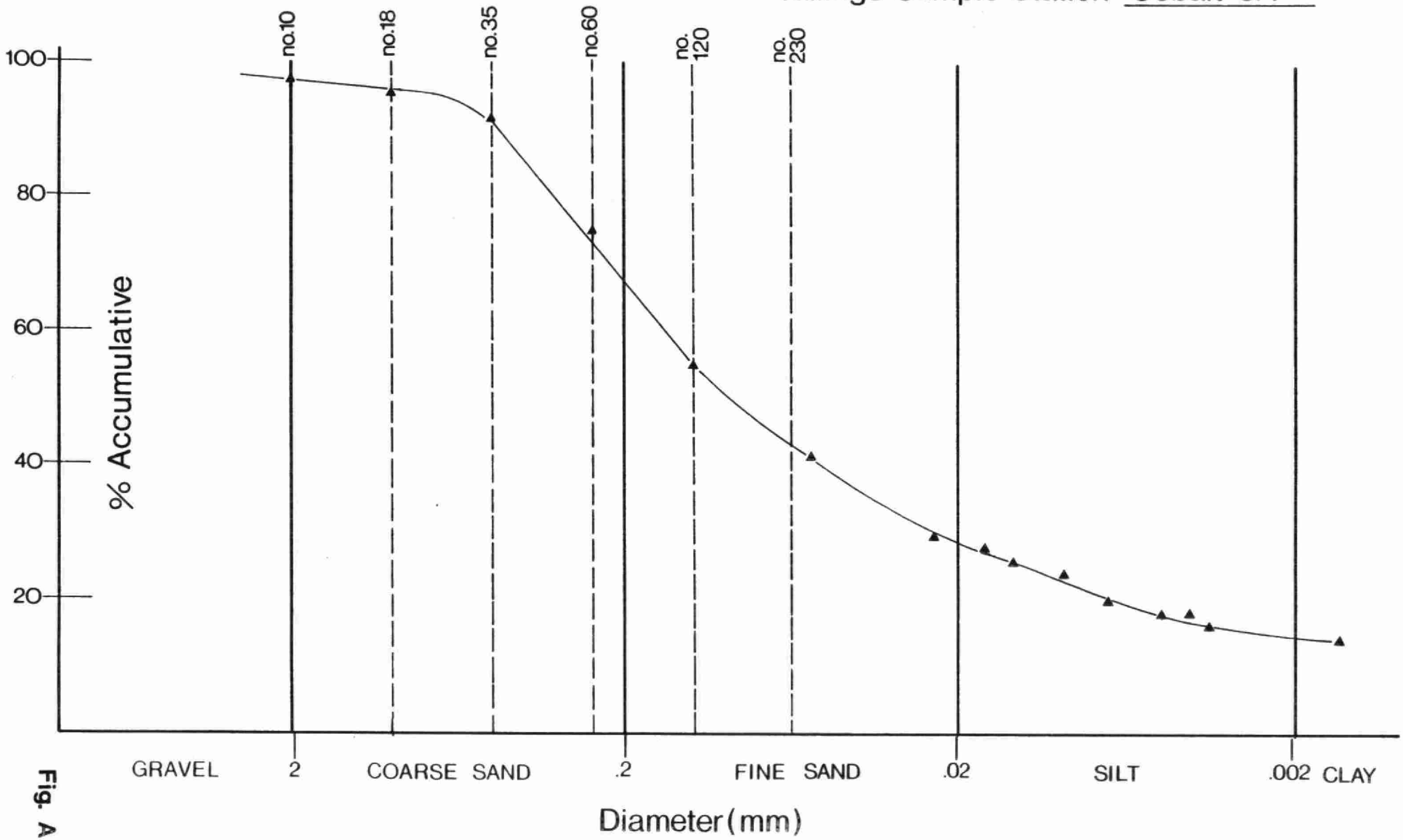


Fig. A - 12

HEAVY METAL MOBILIZATION AND BIOAVAILABILITY – COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

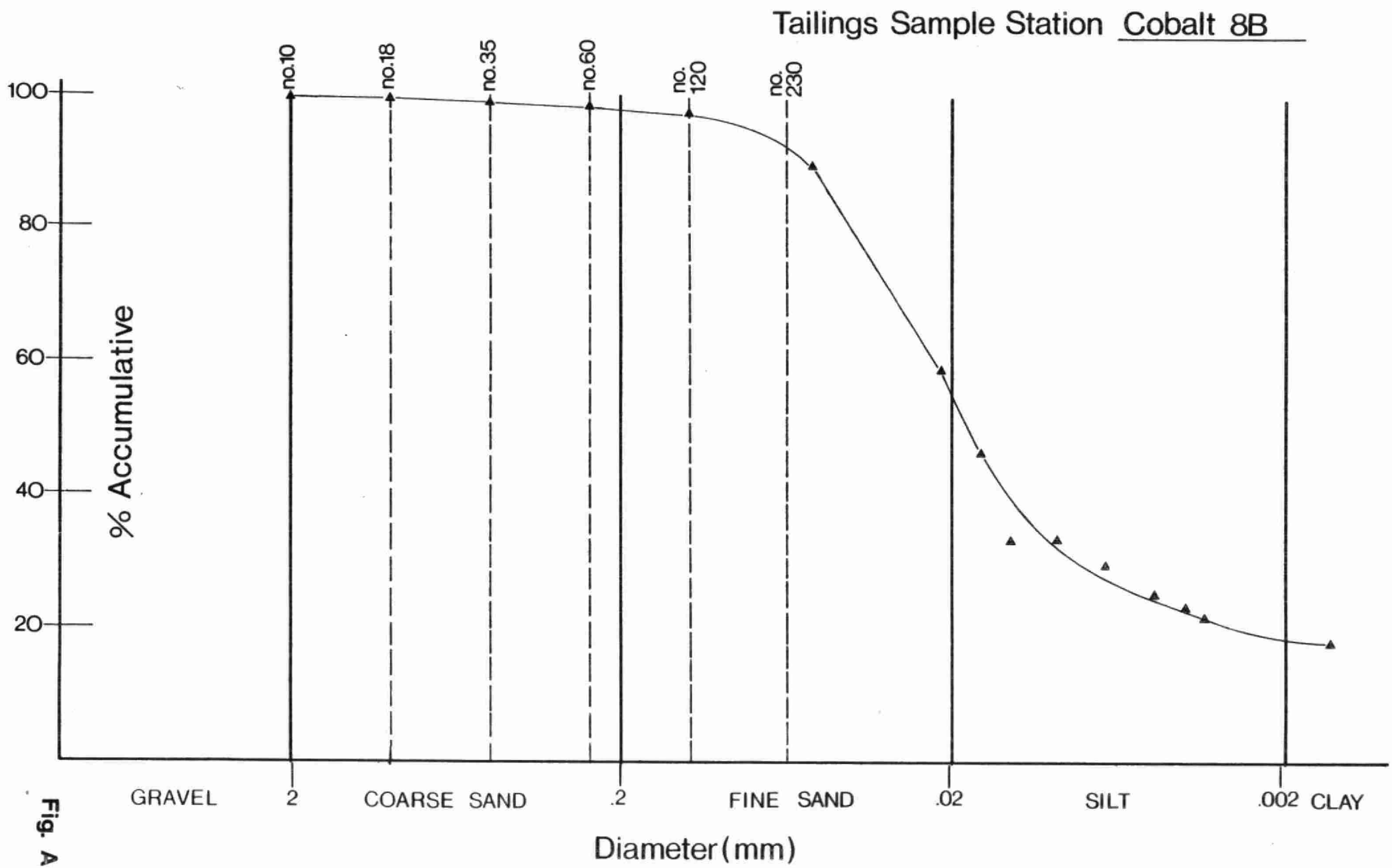
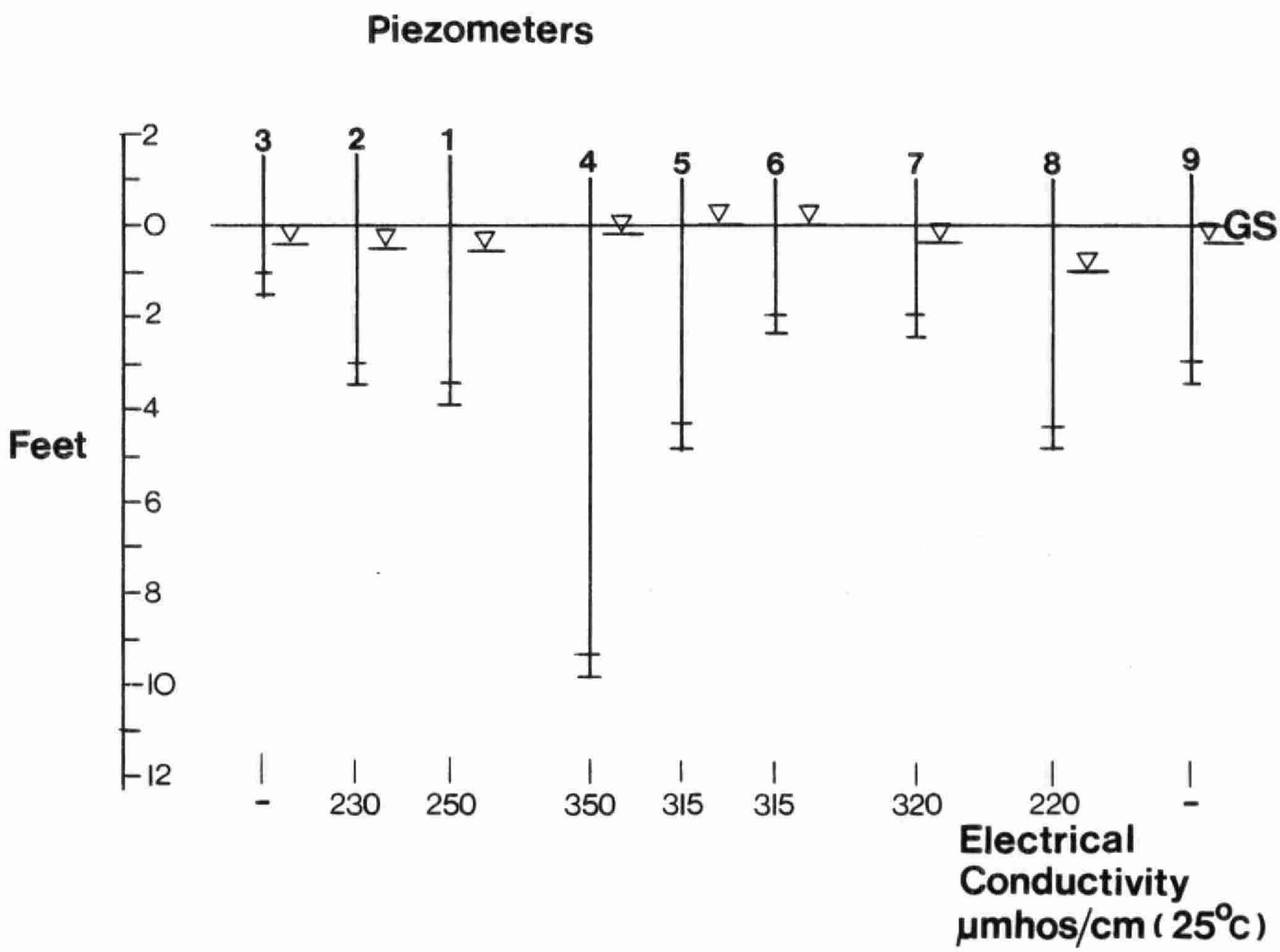


Fig. A - 13

GROUNDWATER HYDROLOGY SITE 4
Oct.'83



NOTE: These groundwater levels were taken immediately following installation of piezometers and therefore do not represent stabilized levels.

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

Tailings Sample Station Cobalt 10A

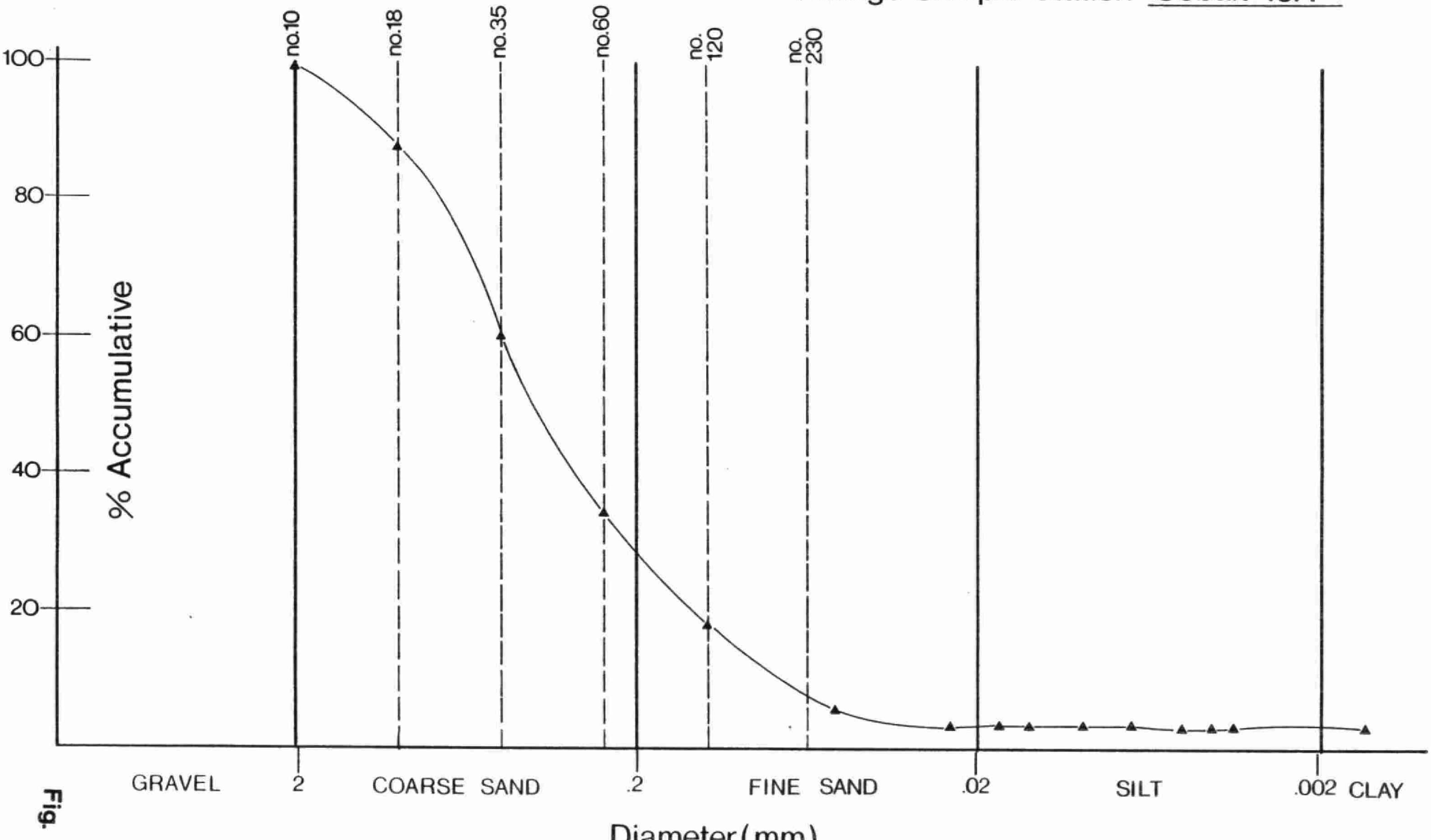


Fig. A - 15

HEAVY METAL MOBILIZATION
AND BIOAVAILABILITY –
COBALT MINE TAILINGS

PARTICLE SIZE DISTRIBUTION CURVE

Tailings Sample Station Cobalt 10B

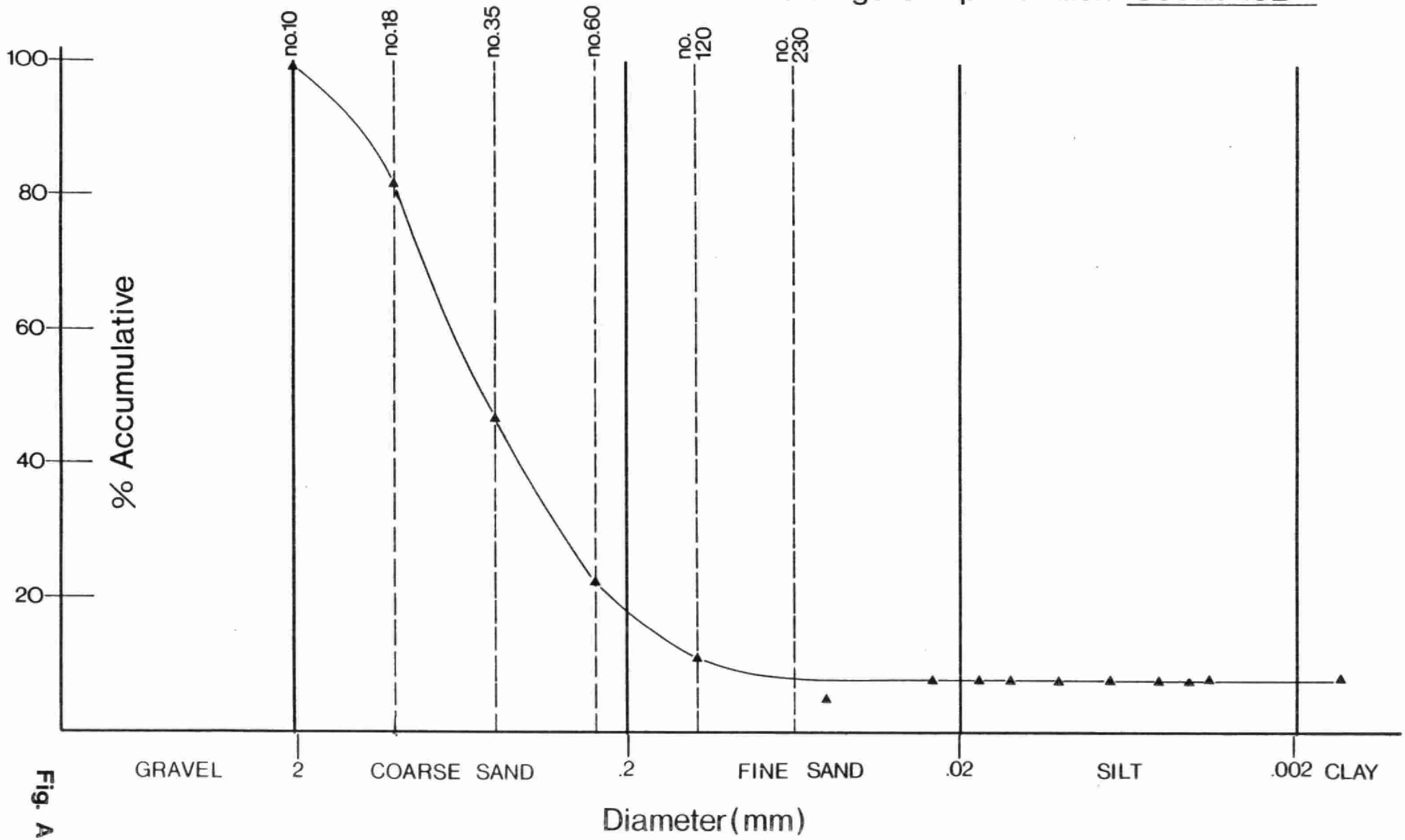


Fig. A - 16

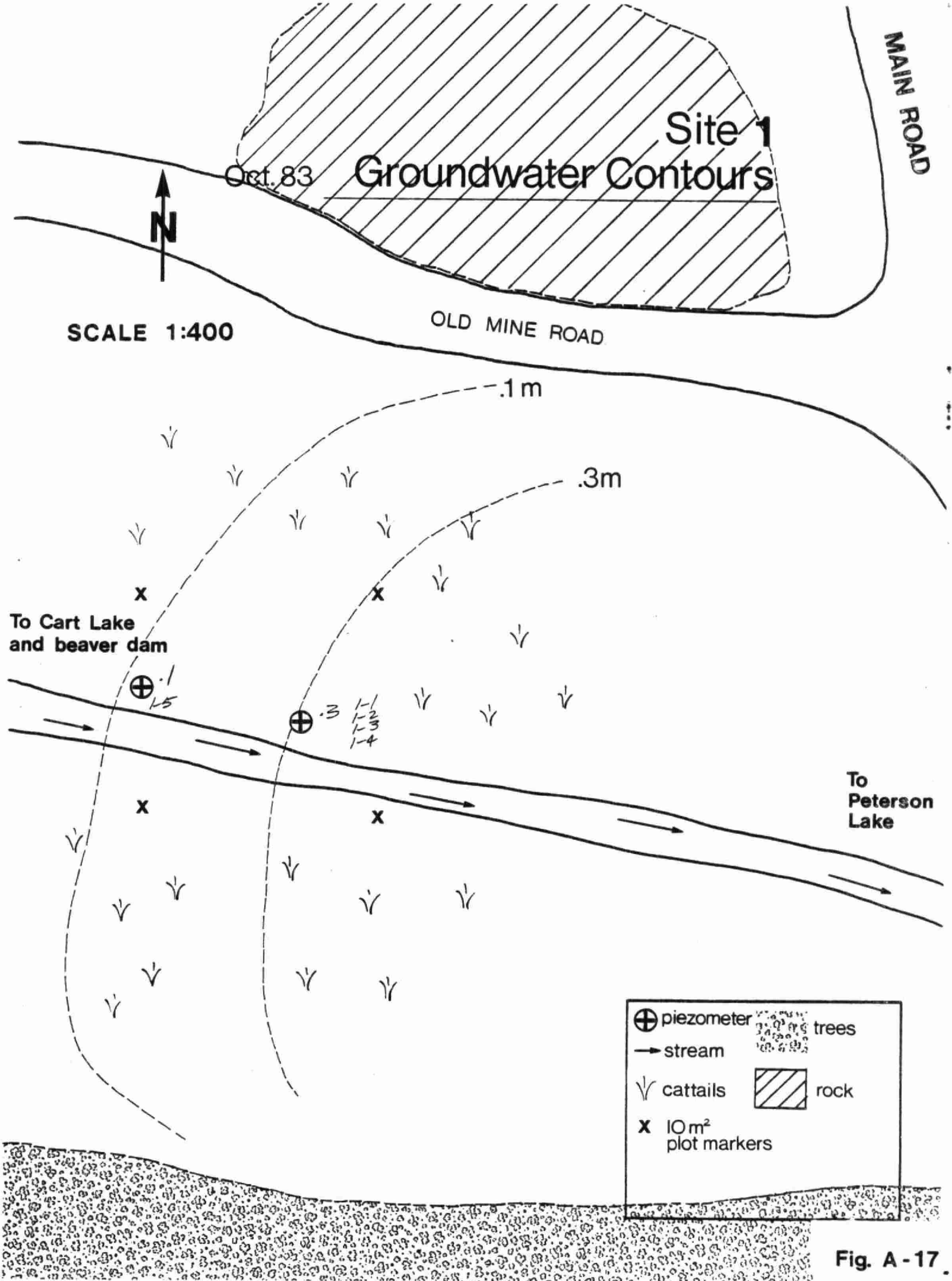

Site 1
Oct. 83 Groundwater Contours
MAIN ROAD
N
SCALE 1:400
OLD MINE ROAD
.1 m
.3m
To Cart Lake
and beaver dam
.1
1-5
.3
1-1
1-2
1-3
1-4
To
Peterson
Lake
piezometer
trees
stream
cattails
rock
X 10 m²
plot markers

Fig. A - 17

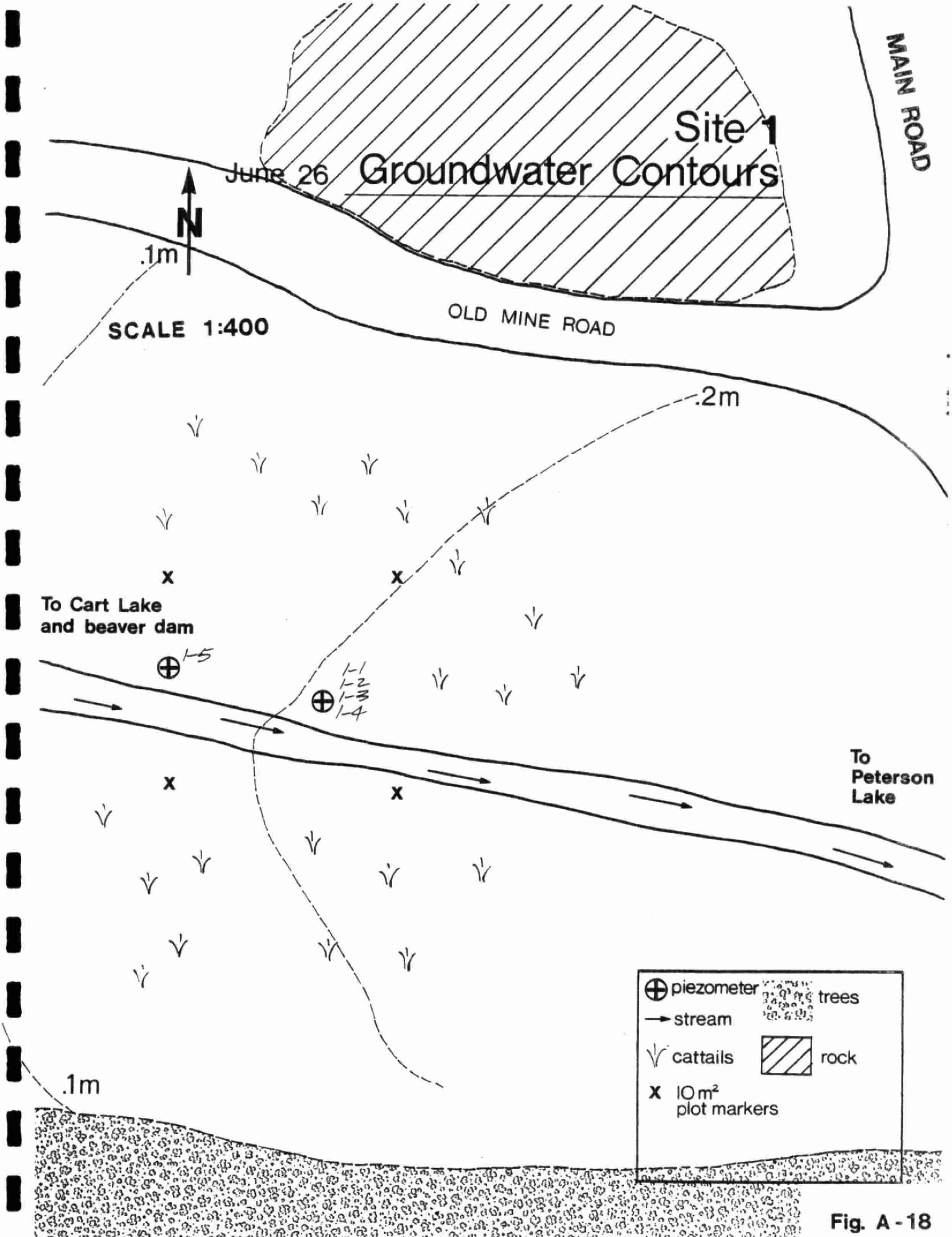

Site 1
June 26 Groundwater Contours
MAIN ROAD
N
.1m
SCALE 1:400
OLD MINE ROAD
.2m
To Cart Lake
and beaver dam
1-5
1-1
1-2
1-3
1-4
To
Peterson
Lake
.1m
piezometer
stream
cattails
10 m²
plot markers
trees
rock

Fig. A - 18

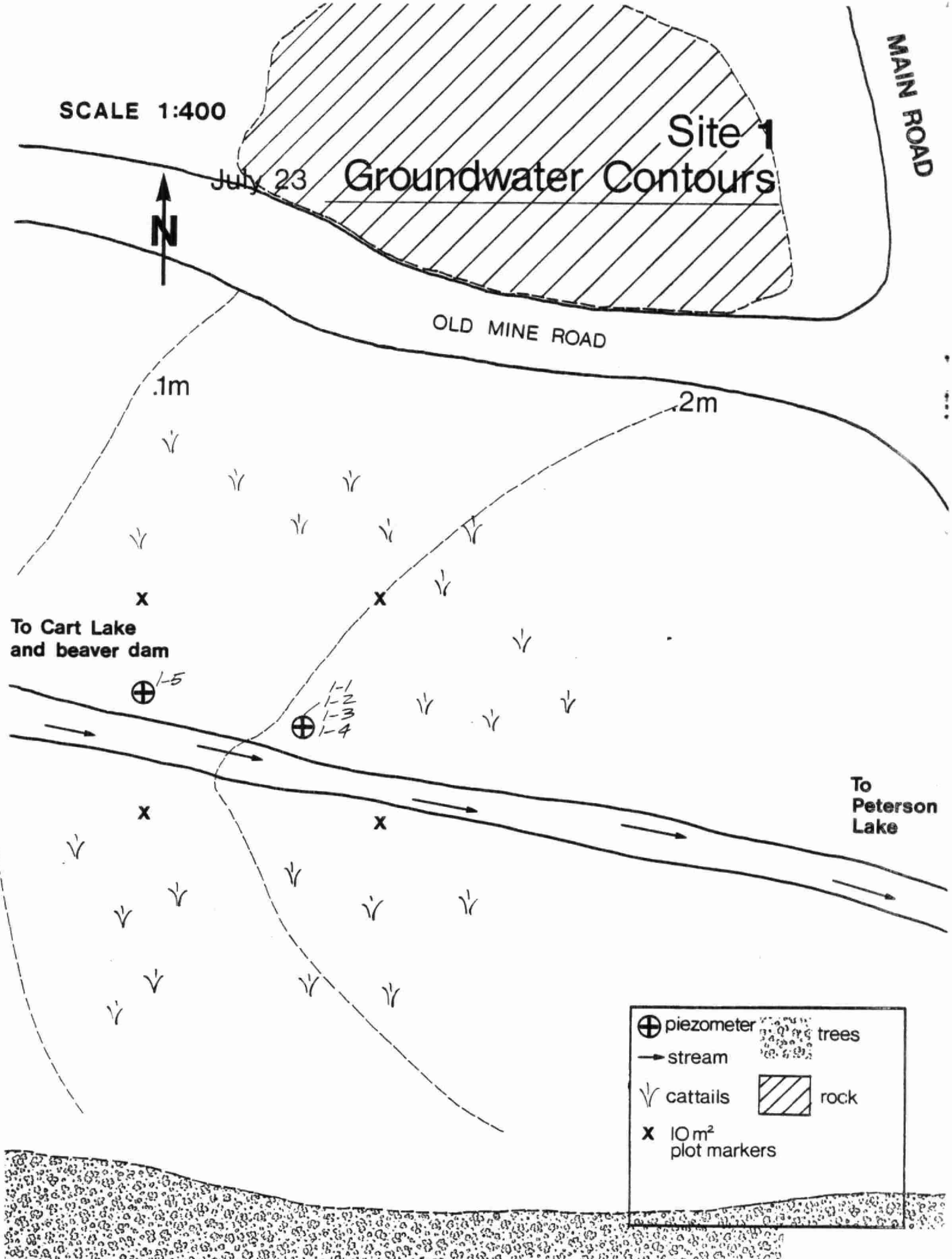
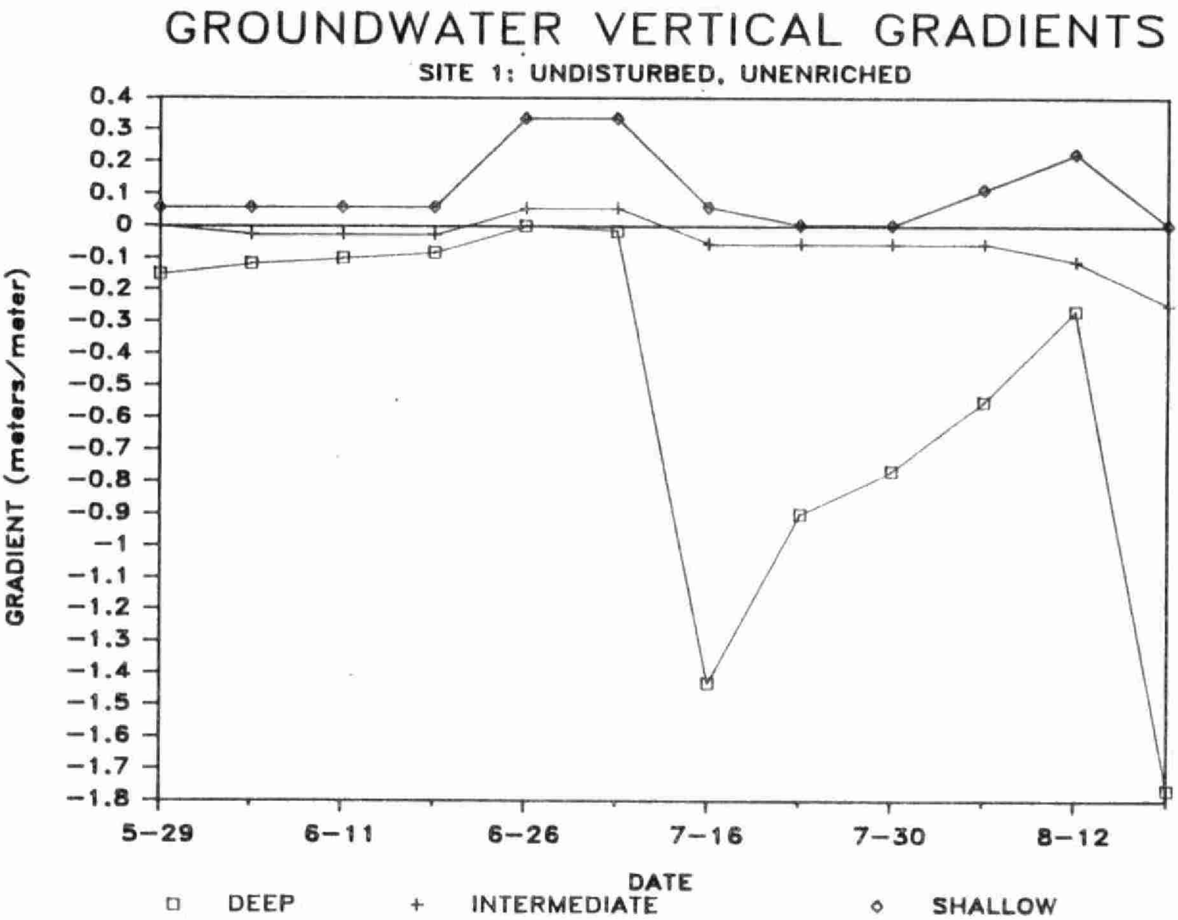
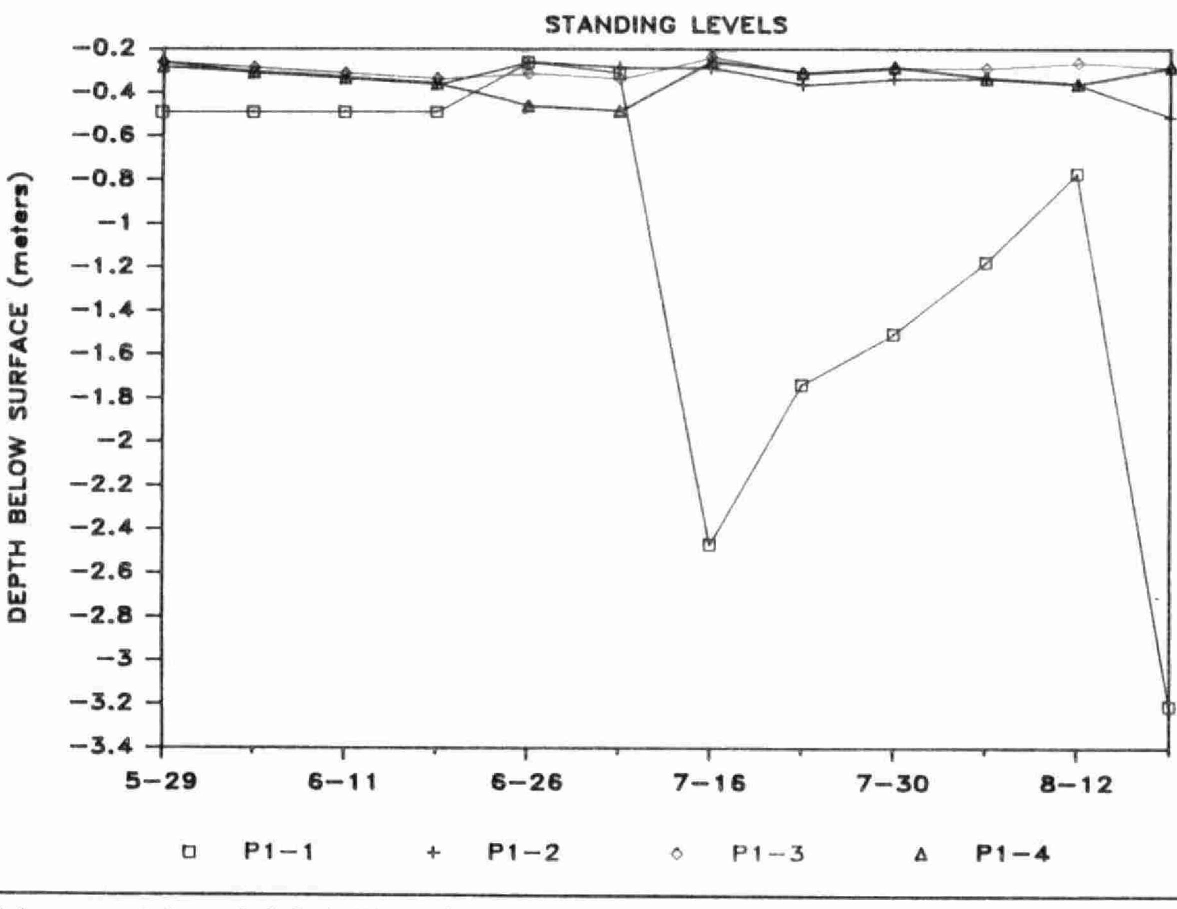
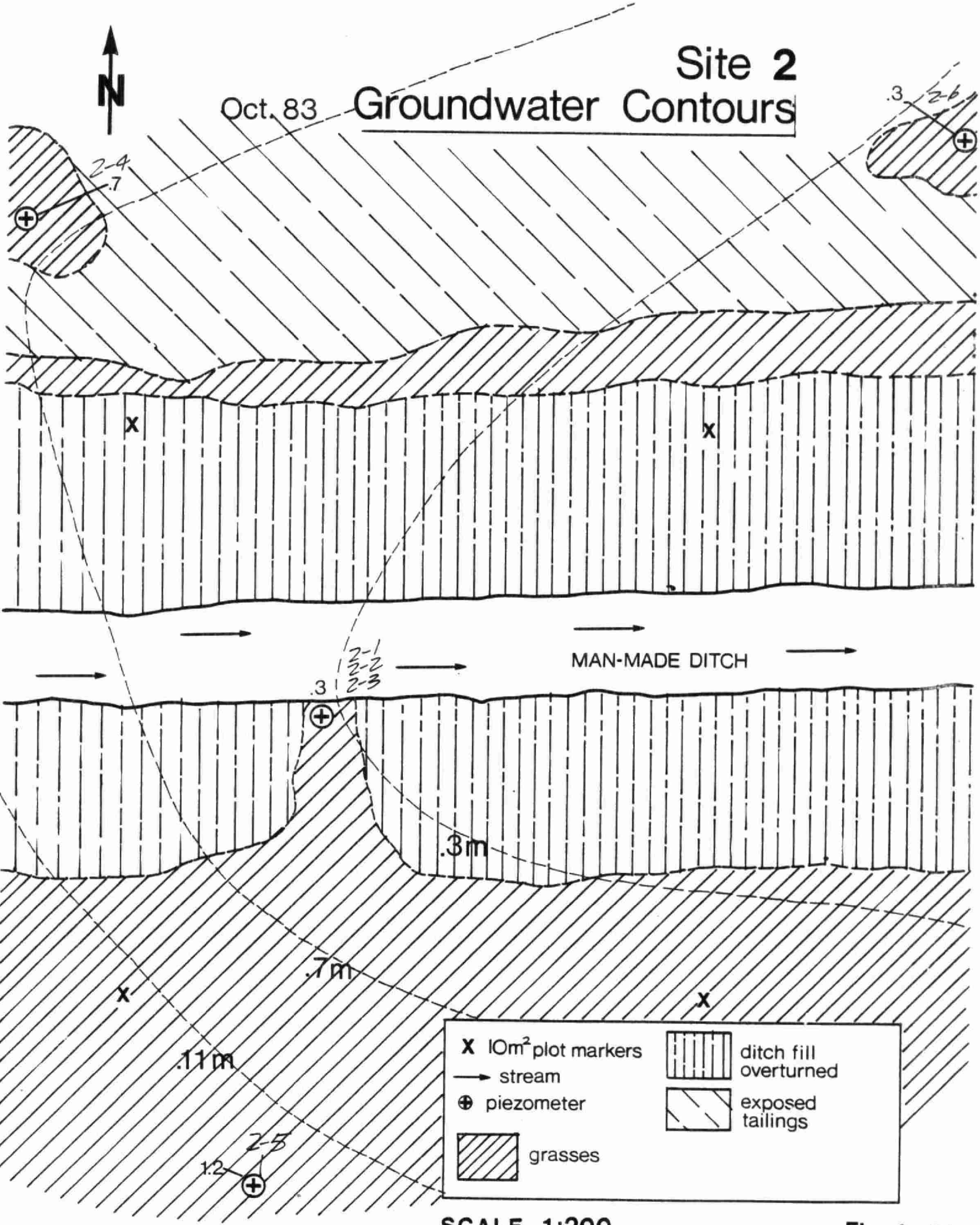

SCALE 1:400
Site 1
July 23 Groundwater Contours
MAIN ROAD
N
OLD MINE ROAD
.1m
.2m
To Cart Lake and beaver dam
1-5
1-1
1-2
1-3
1-4
To Peterson Lake
piezometer
trees
stream
cattails
rock
10 m²
plot markers

Fig. A-19

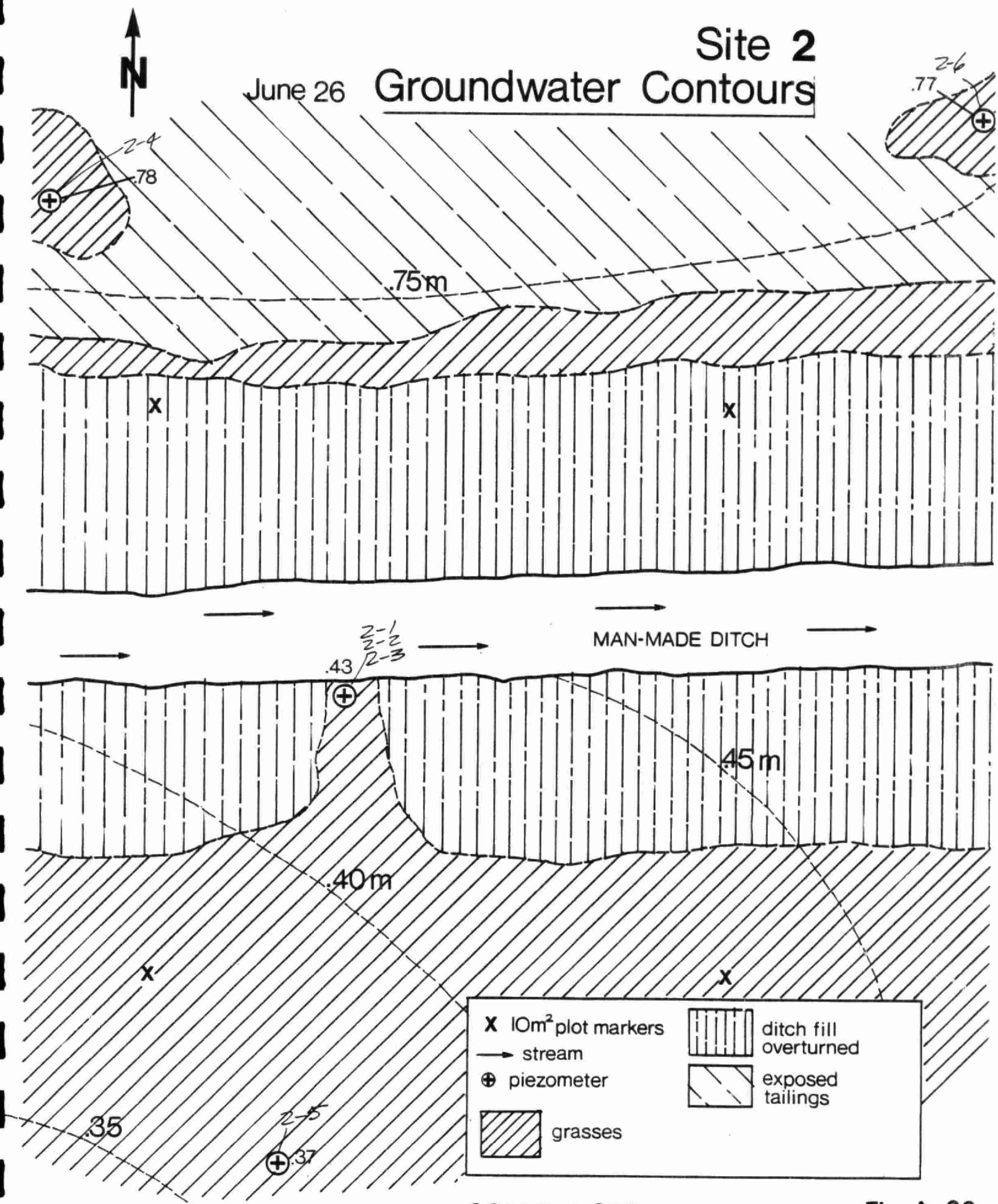

GROUNDWATER VERTICAL GRADIENTS
SITE 1: UNDISTURBED, UNENRICHED
GRADIENT (meters/meter)
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1
−1.1
−1.2
−1.3
−1.4
−1.5
−1.6
−1.7
−1.8
5−29
6−11
6−26
7−16
7−30
8−12
DATE
DEEP
INTERMEDIATE
SHALLOW


STANDING LEVELS
DEPTH BELOW SURFACE (meters)
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2
−2.2
−2.4
−2.6
−2.8
−3
−3.2
−3.4
5−29
6−11
6−26
7−16
7−30
8−12
P1−1
P1−2
P1−3
P1−4



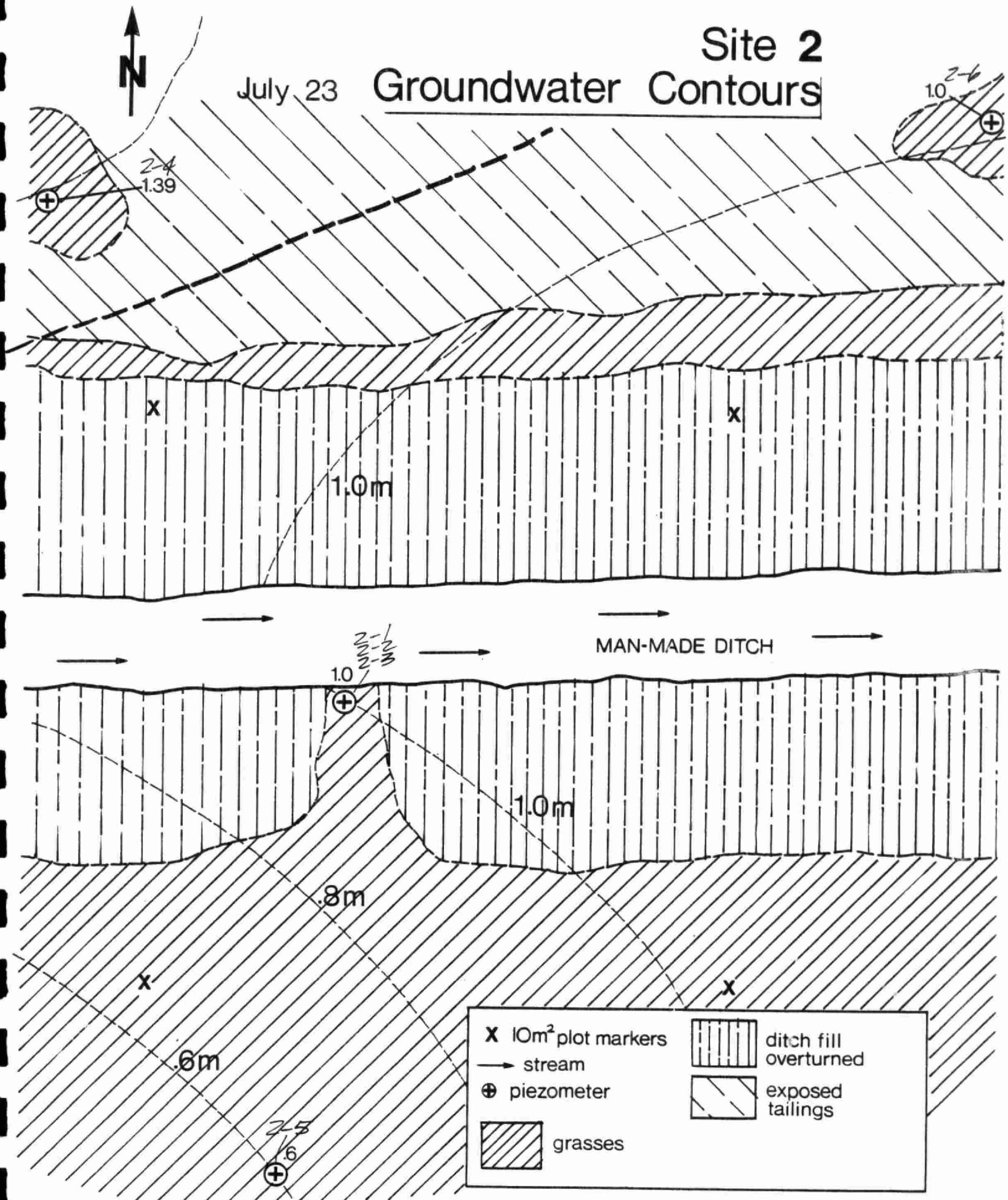
N
Site 2
Oct. 83
Groundwater Contours
.3
2-6
2-4
.7
X
X
MAN-MADE DITCH
2-1
2-2
2-3
.3
.3m
.7m
X
X
.11m
2-5
1.2
X 10m² plot markers
stream
piezometer
grasses
ditch fill overturned
exposed tailings
SCALE 1:200

Fig. A-21



SCALE 1:200

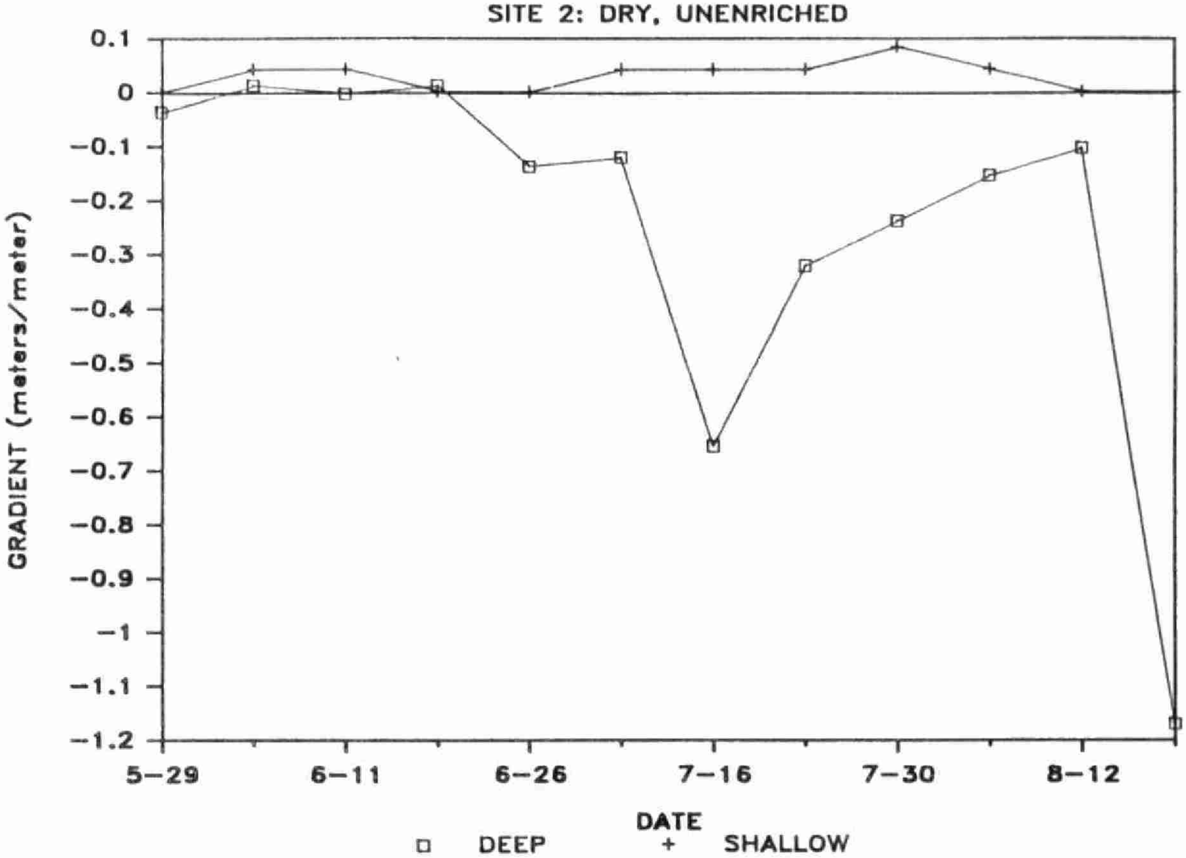
Fig. A - 22

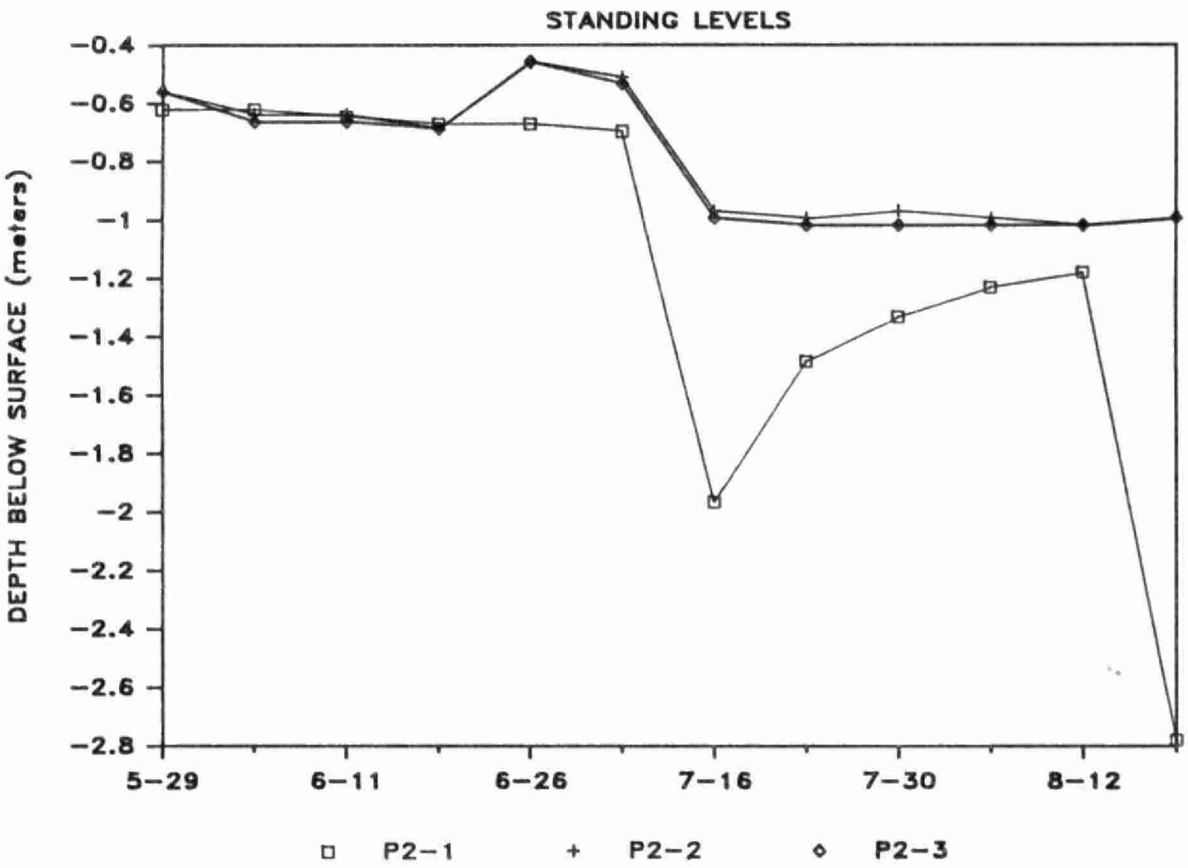


SCALE 1:200

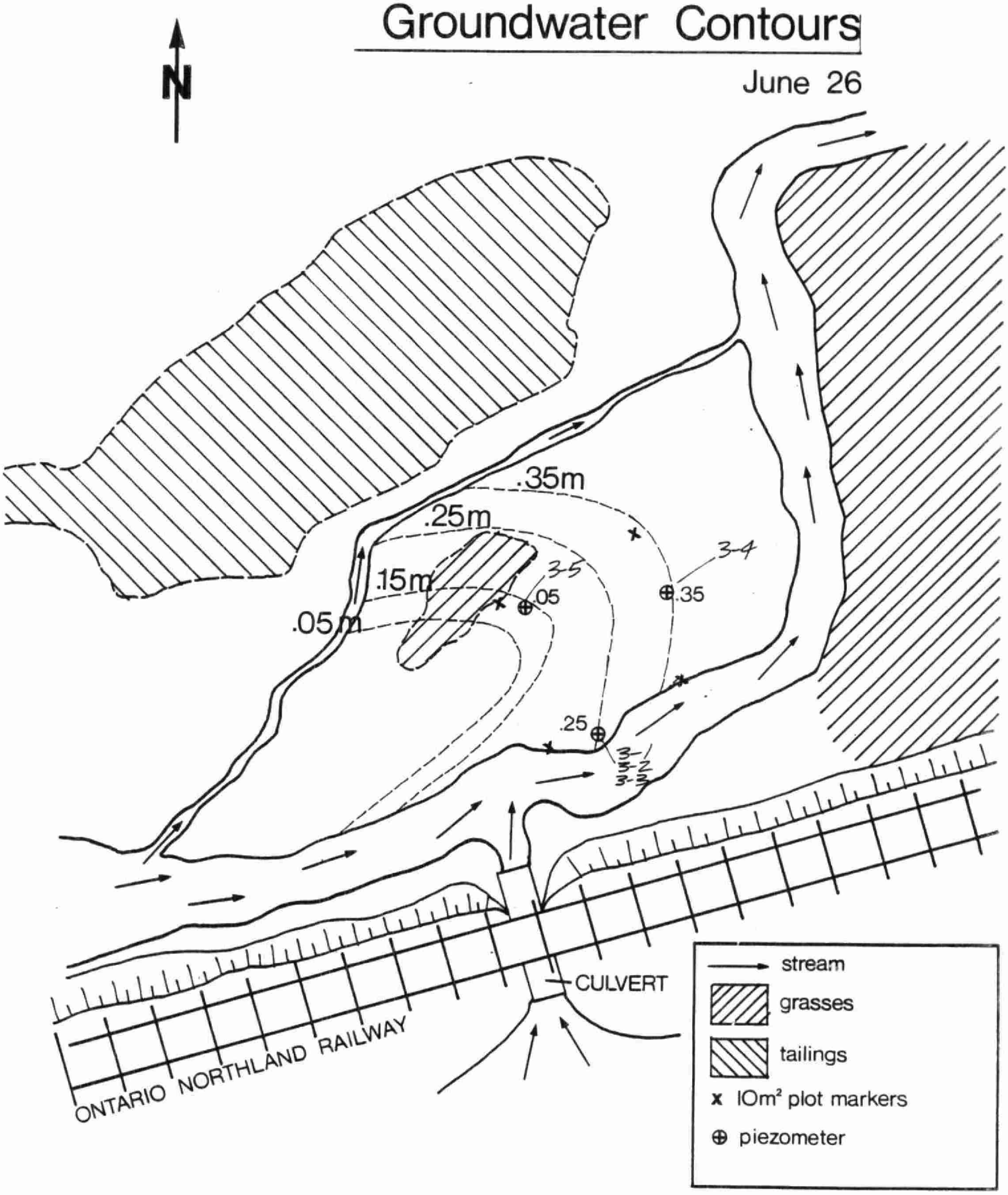
Fig. A-23

GROUNDWATER VERTICAL GRADIENTS





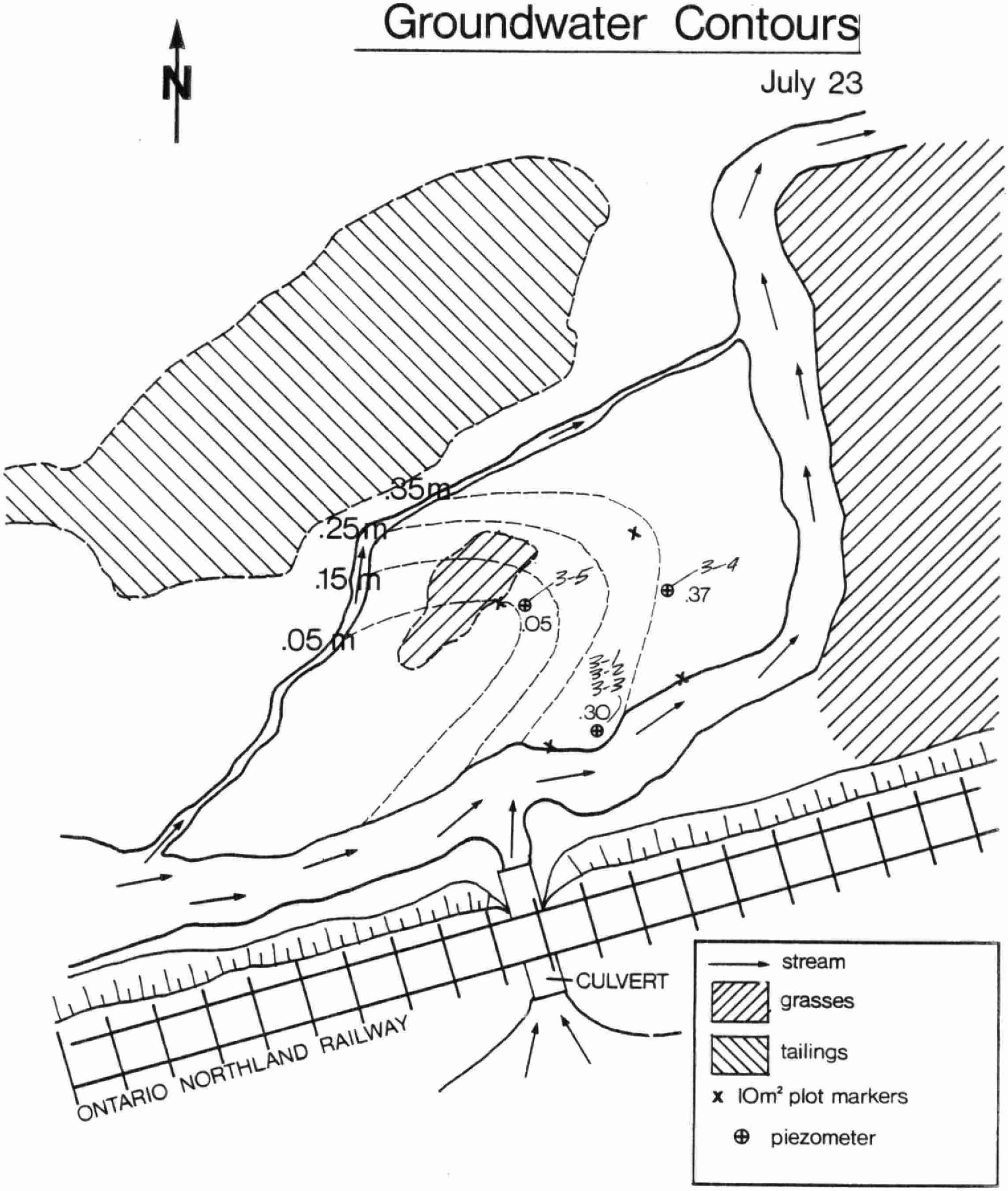
Site 3
Groundwater Contours
June 26



SCALE 1:200 Fig. A - 25

Site 3
Groundwater Contours

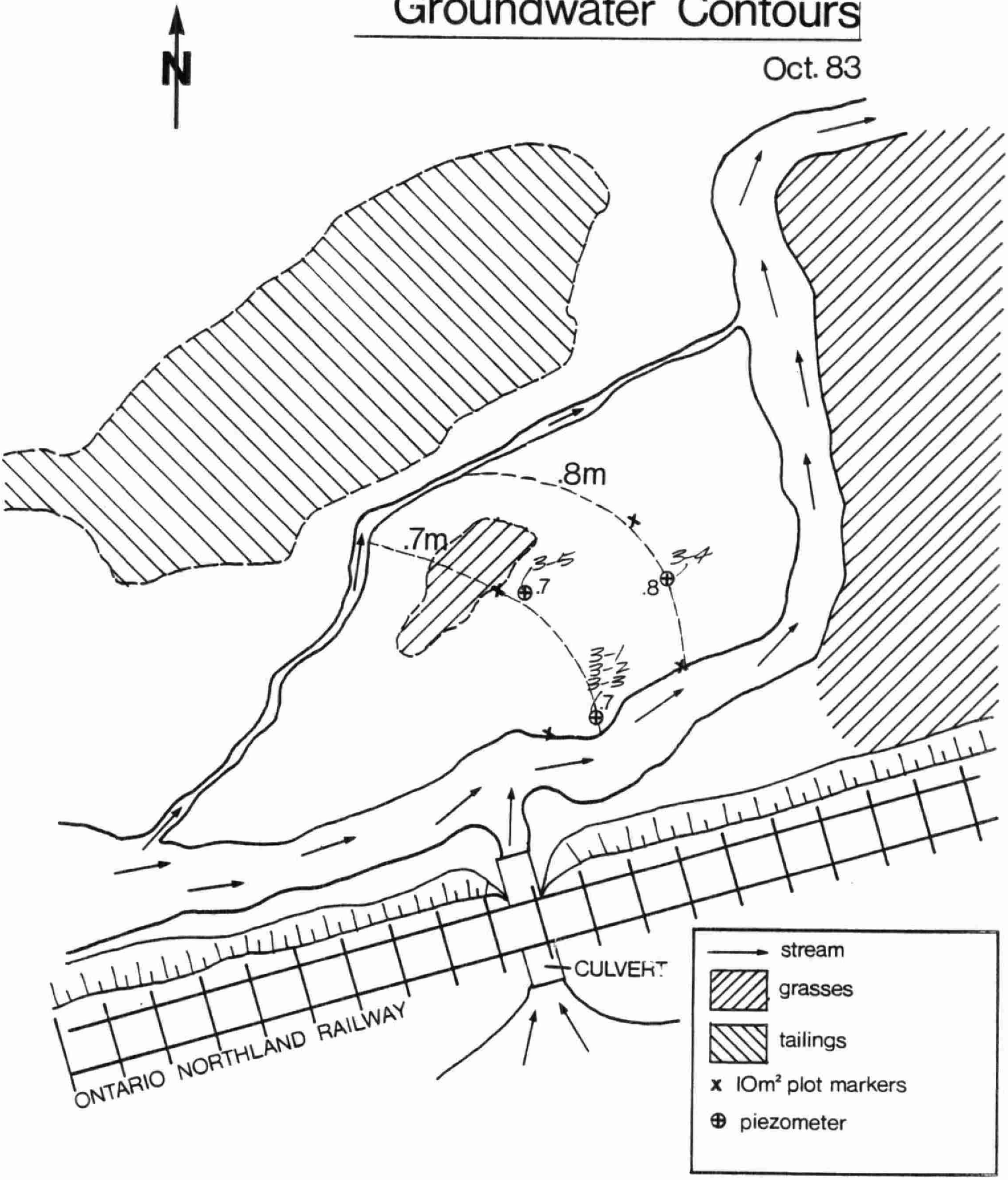
July 23



SCALE 1:200 Fig. A - 26

Site 3
Groundwater Contours

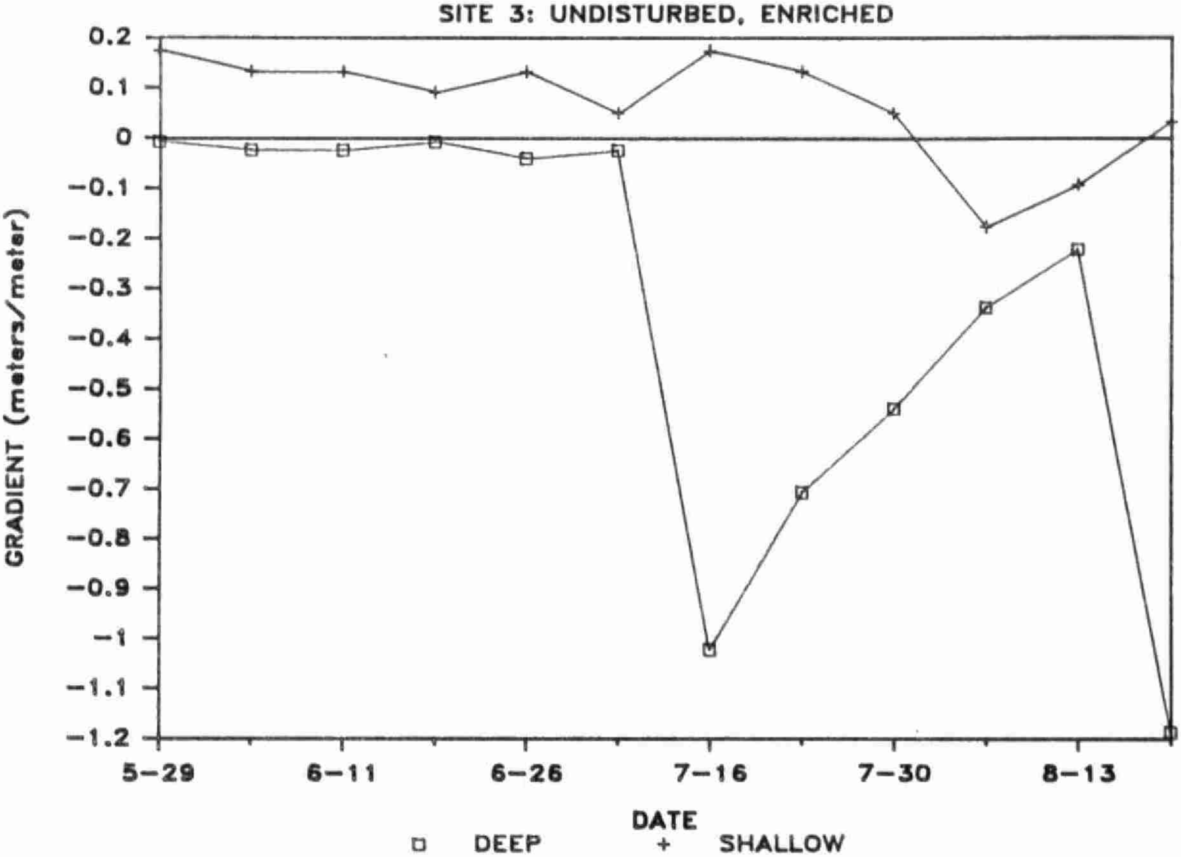
Oct. 83

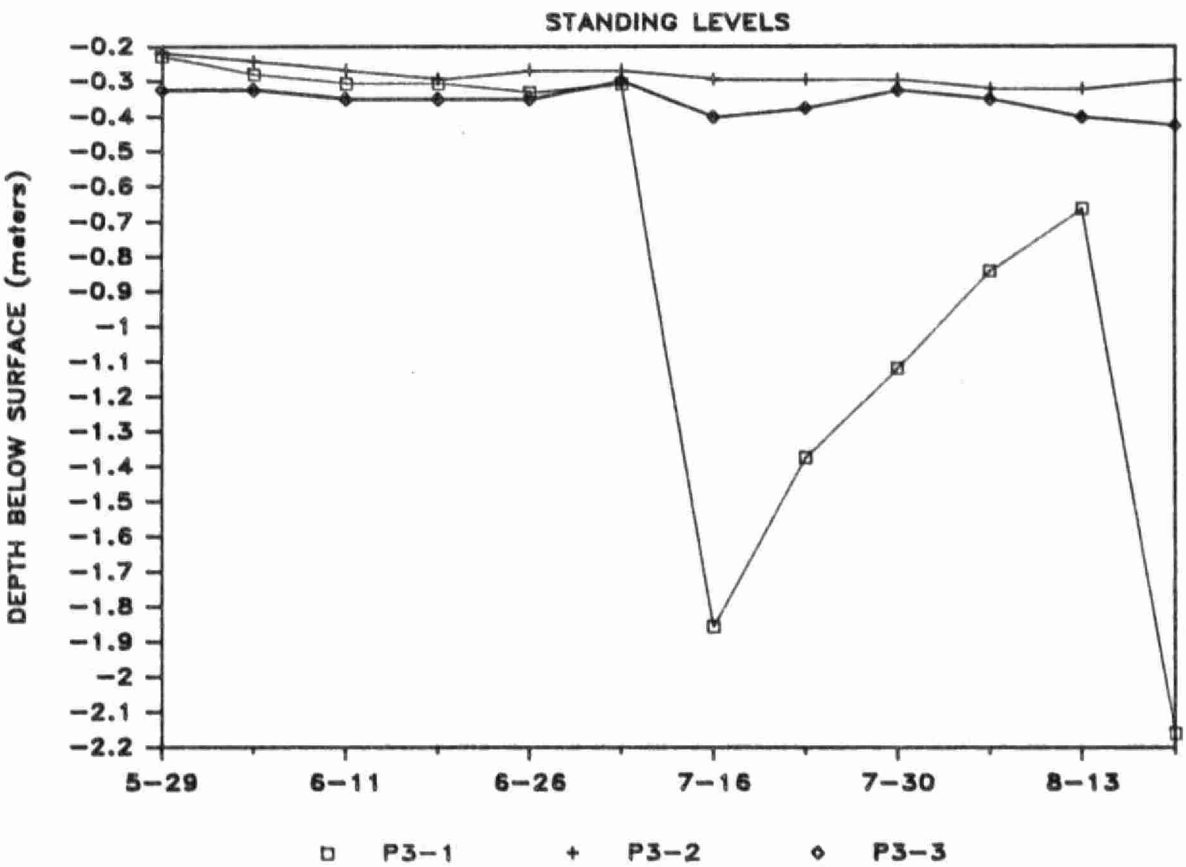


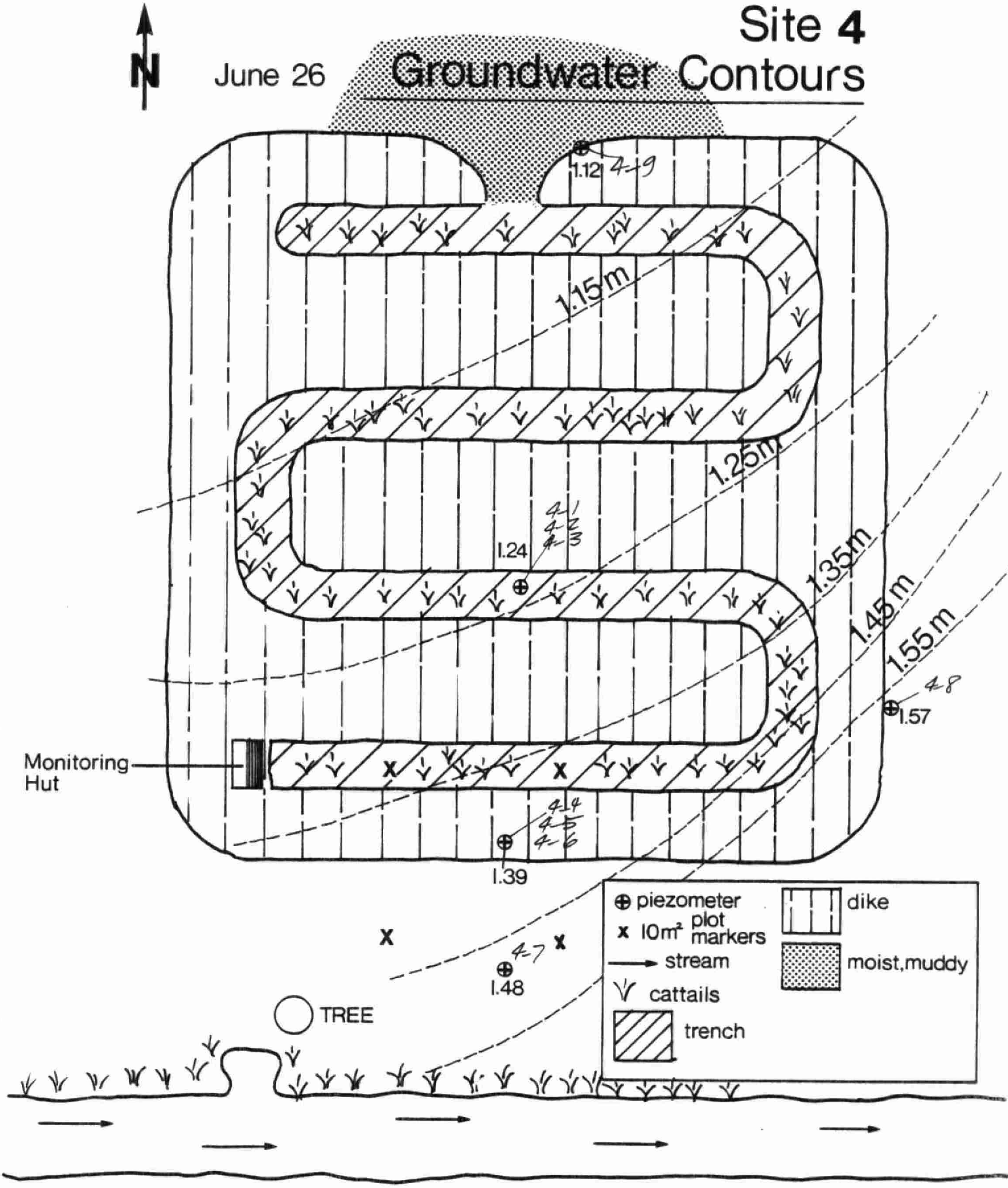
SCALE 1:200

Fig. A - 27

GROUNDWATER VERTICAL GRADIENTS

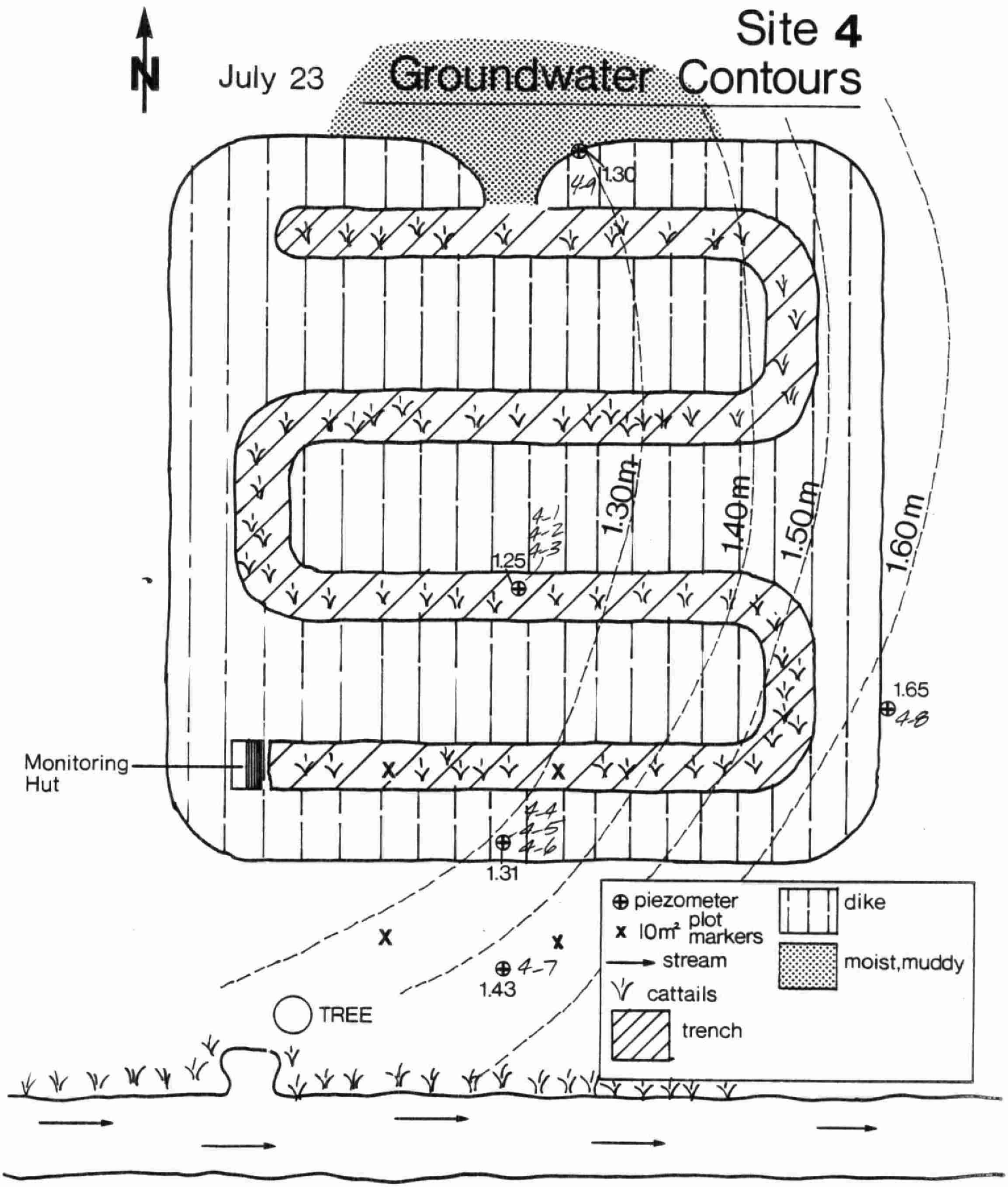






SCALE 1:400

Fig. A-29

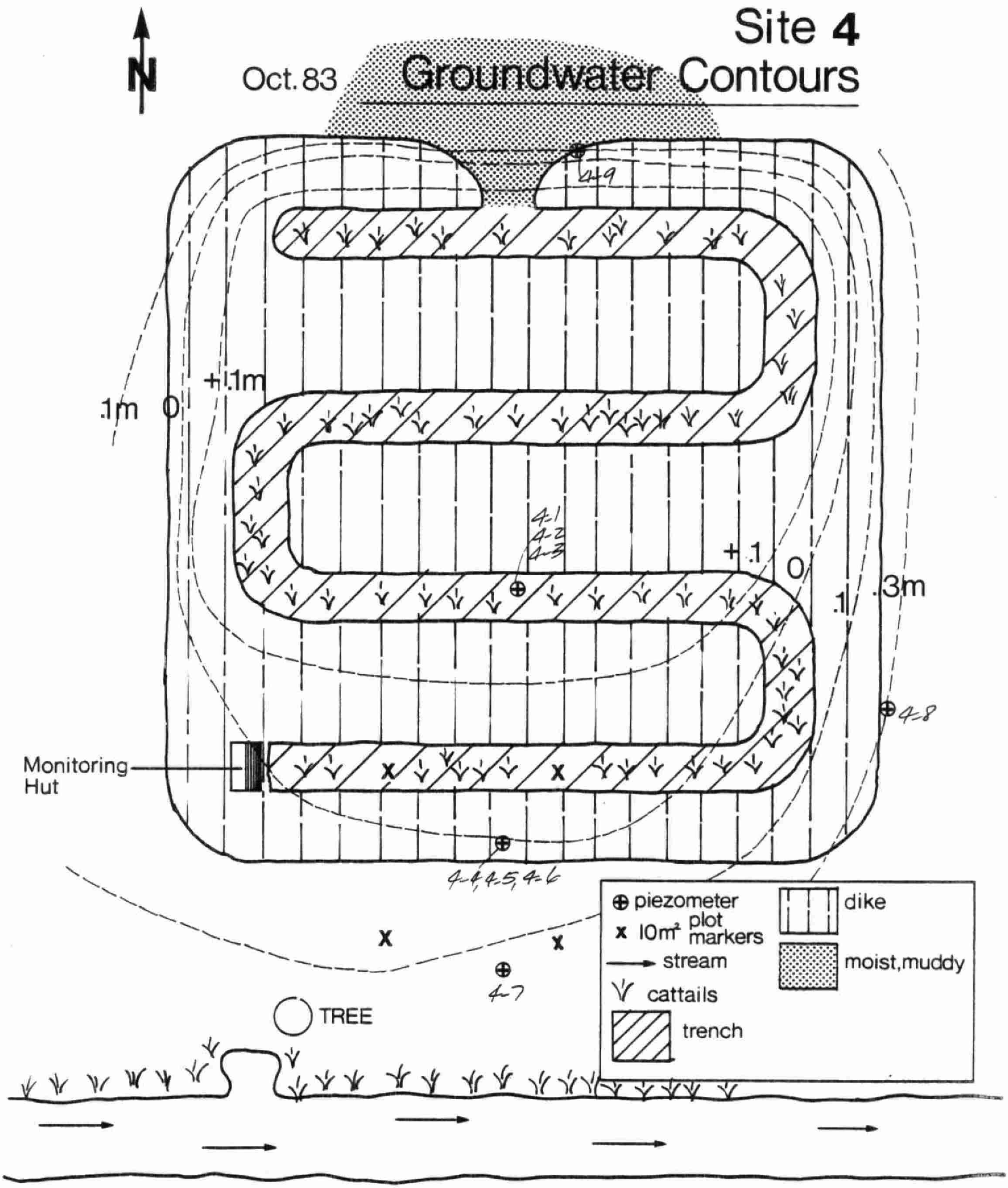


SCALE 1:400

Fig. A-30

Site 4
Groundwater Contours

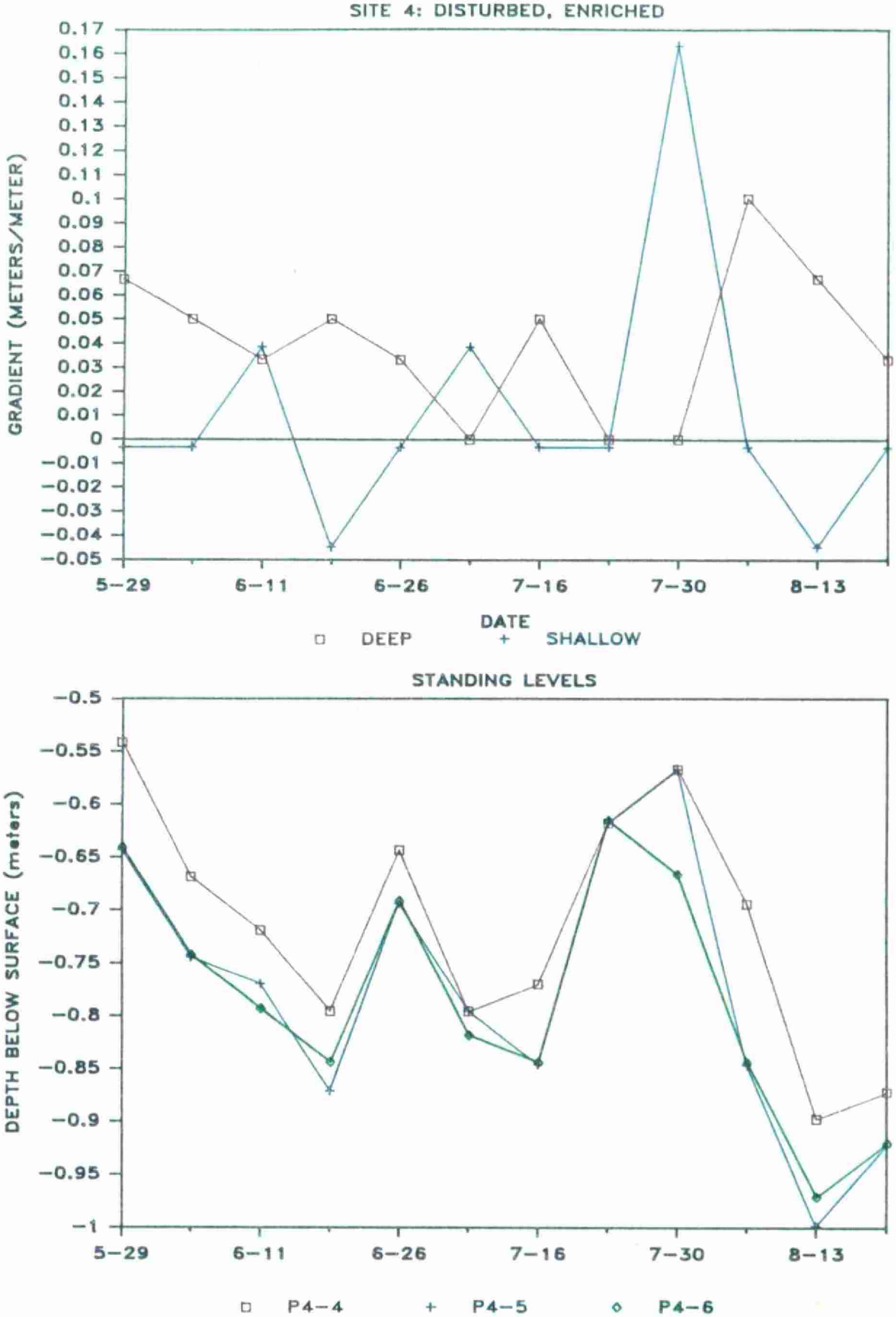
Oct. 83



SCALE 1:400

Fig. A-31

GROUNDWATER VERTICAL GRADIENTS

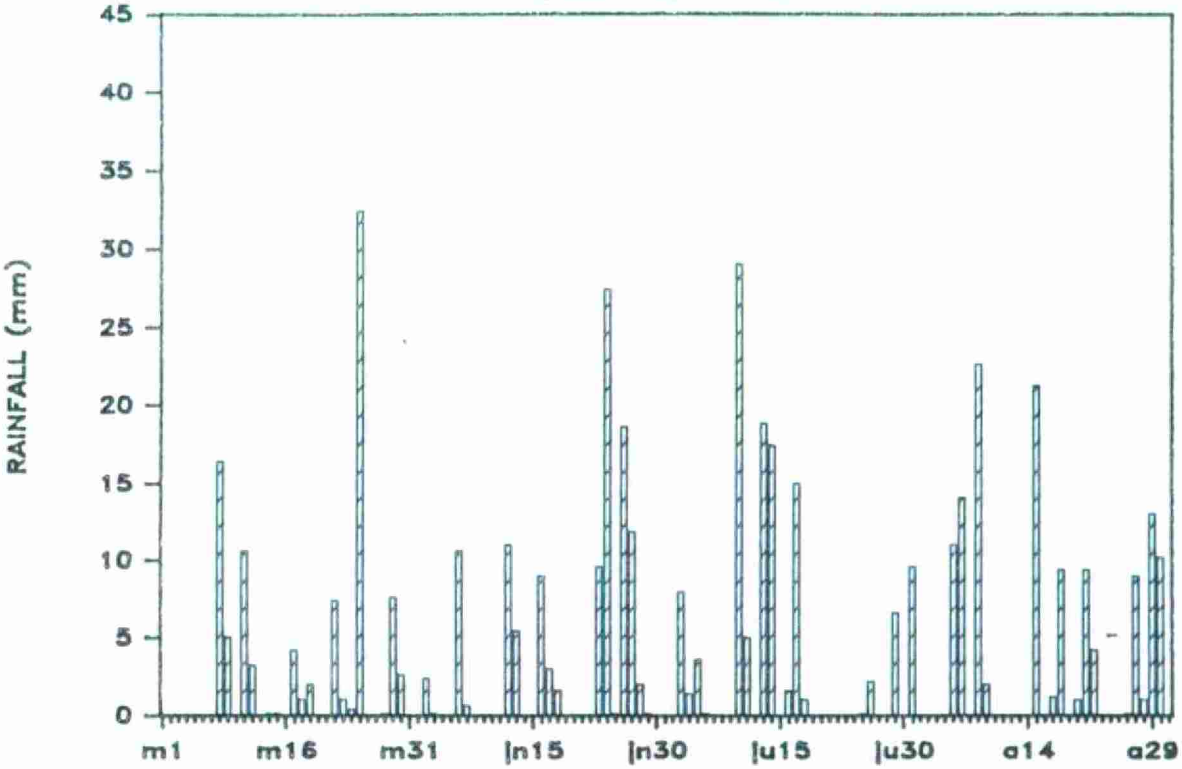


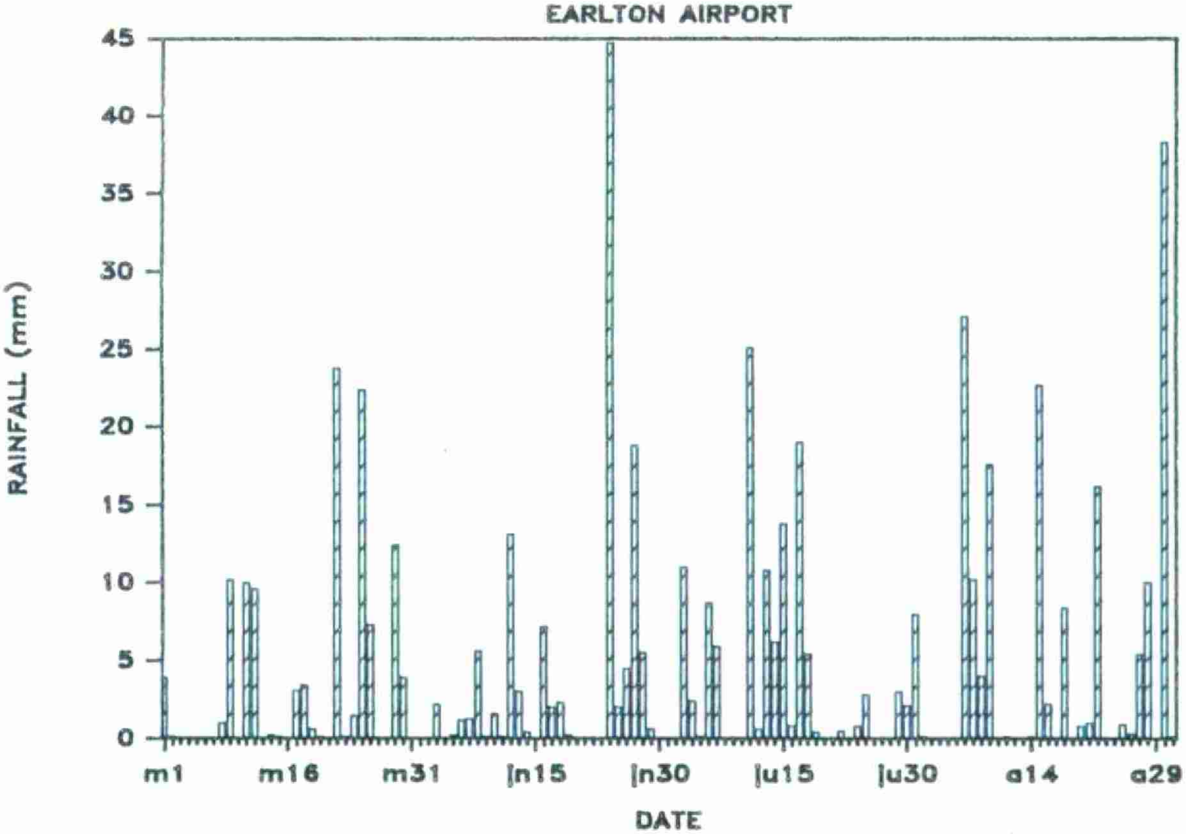
Heavy Metal Mobilization
and Bioavailability
Cobalt Mine Tailings

J E Hanna Associates Inc.

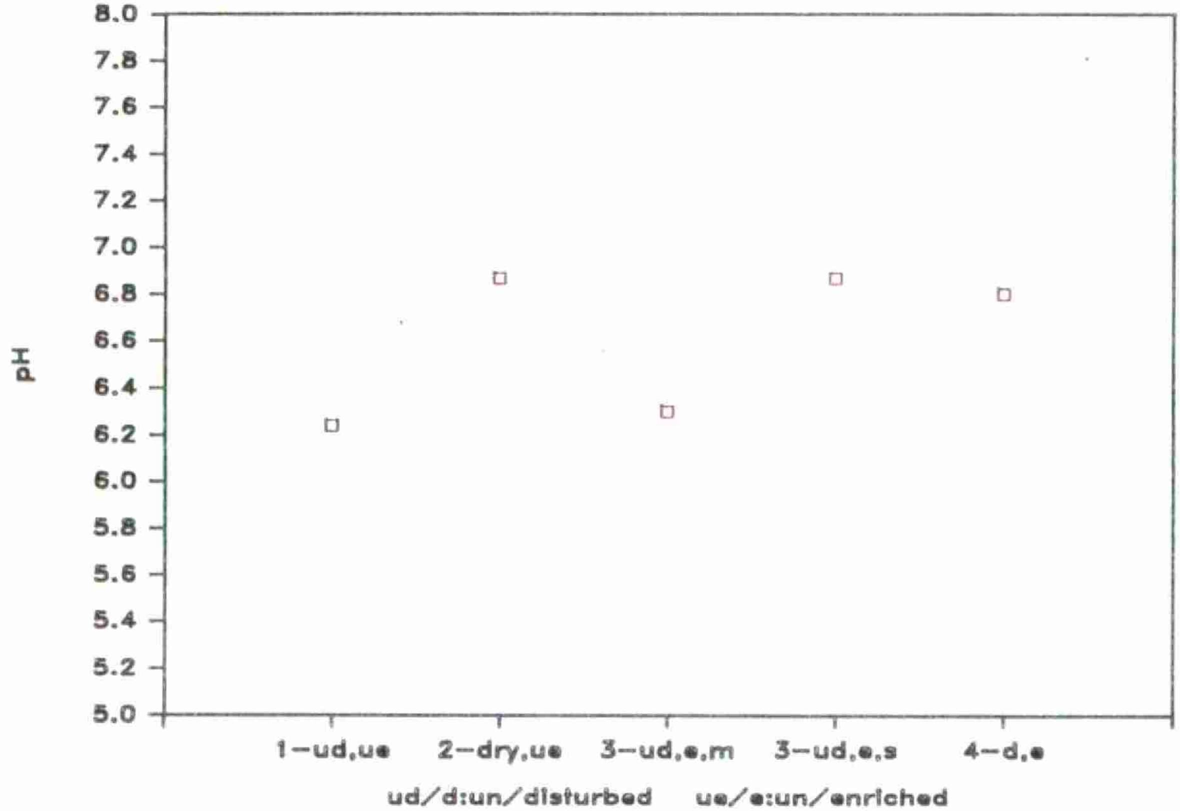
Fig. A - 32

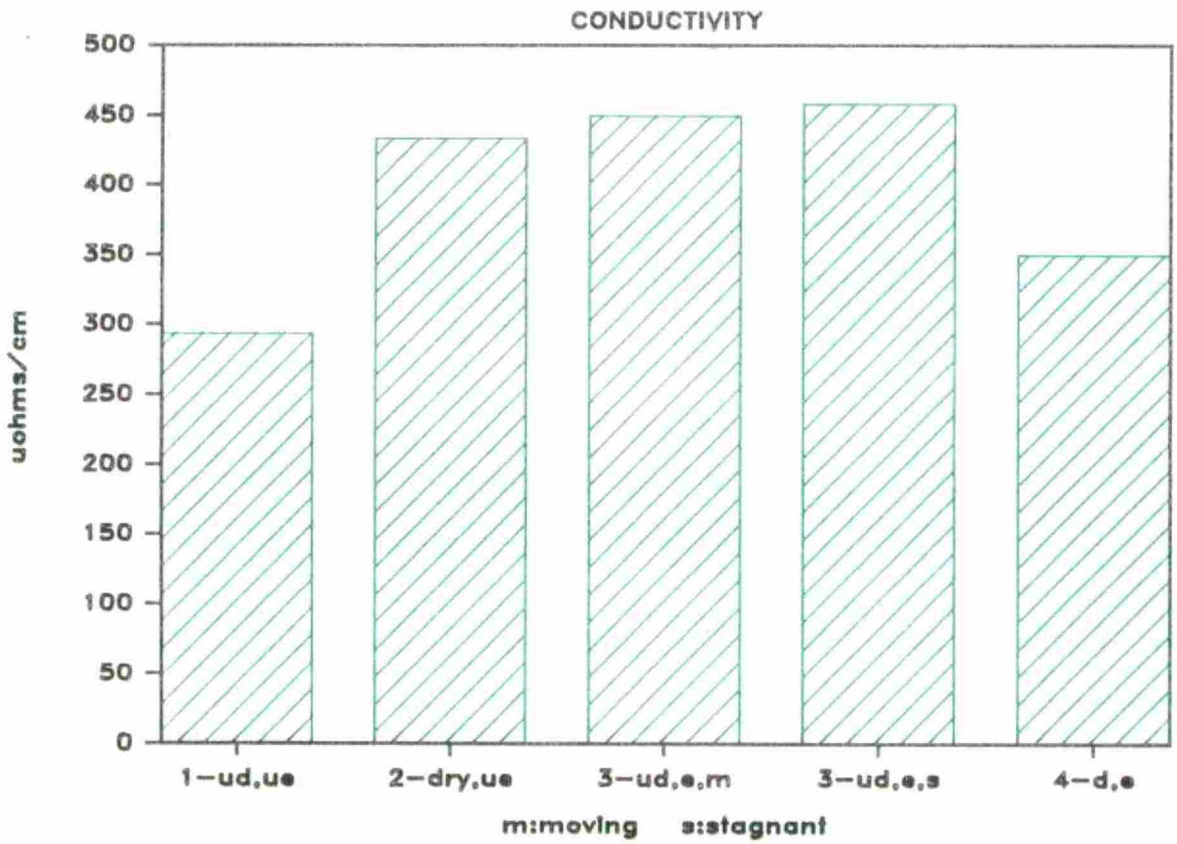
DAILY PRECIPITATION



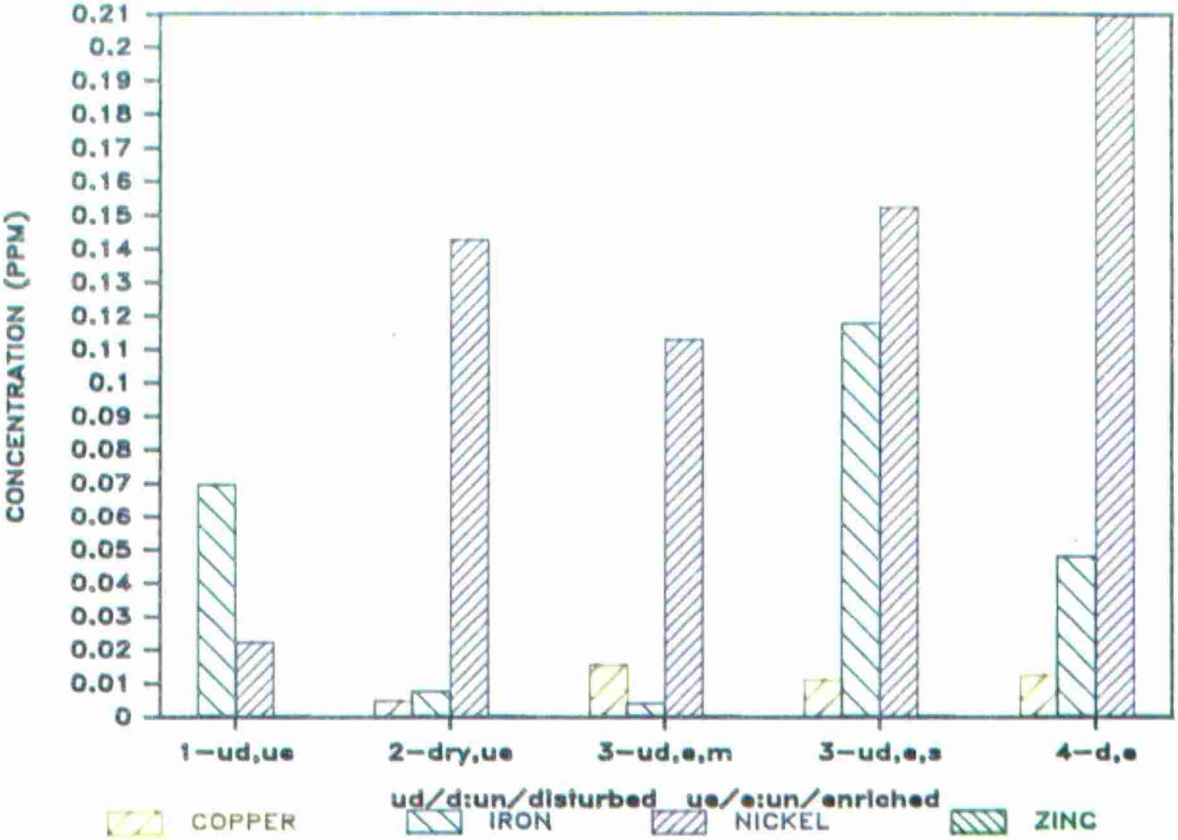


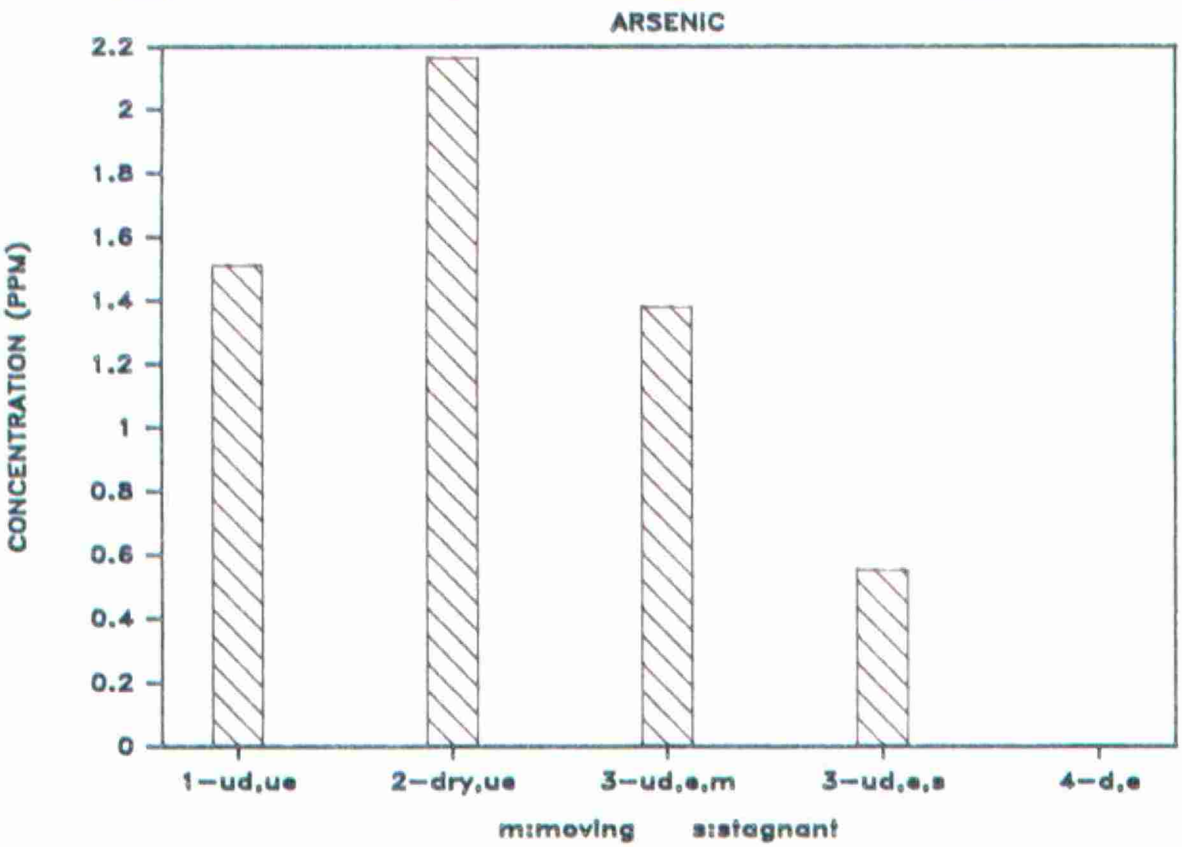
SURFACE WATER QUALITY





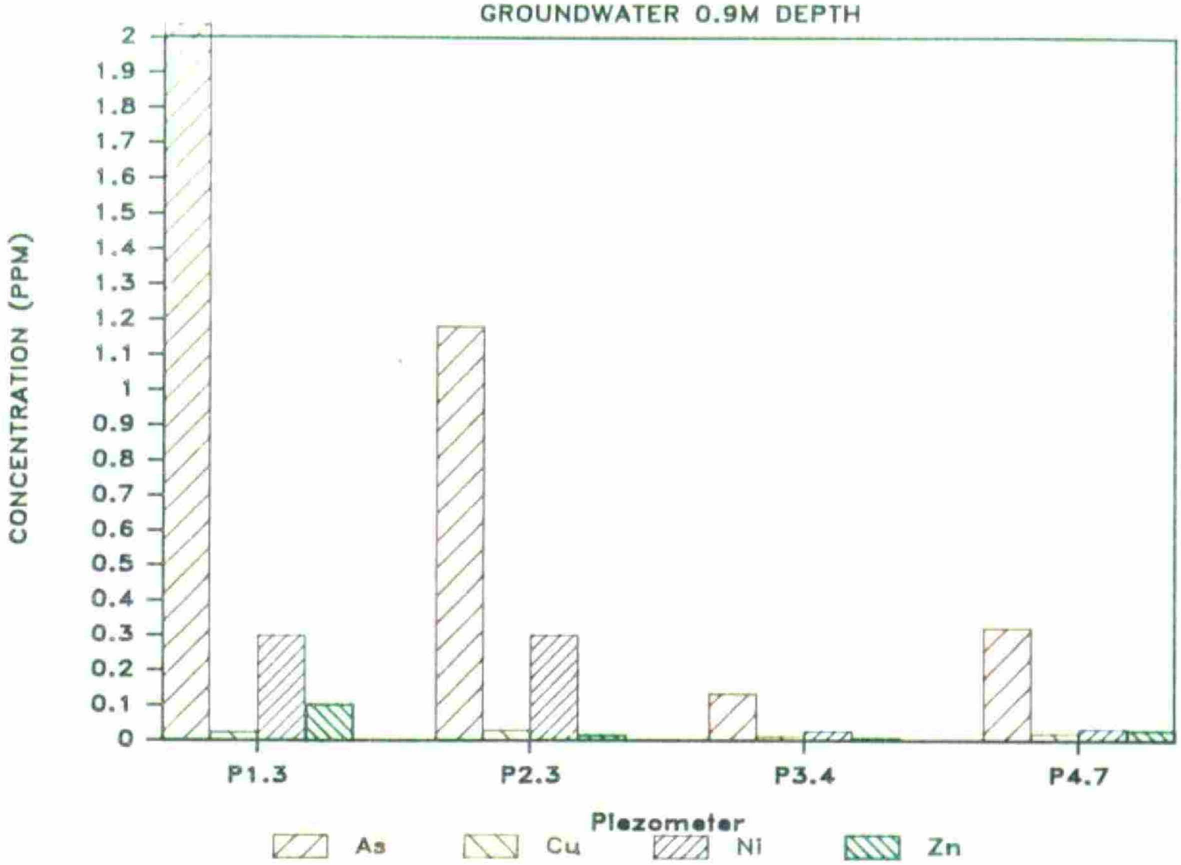
SURFACE WATER QUALITY

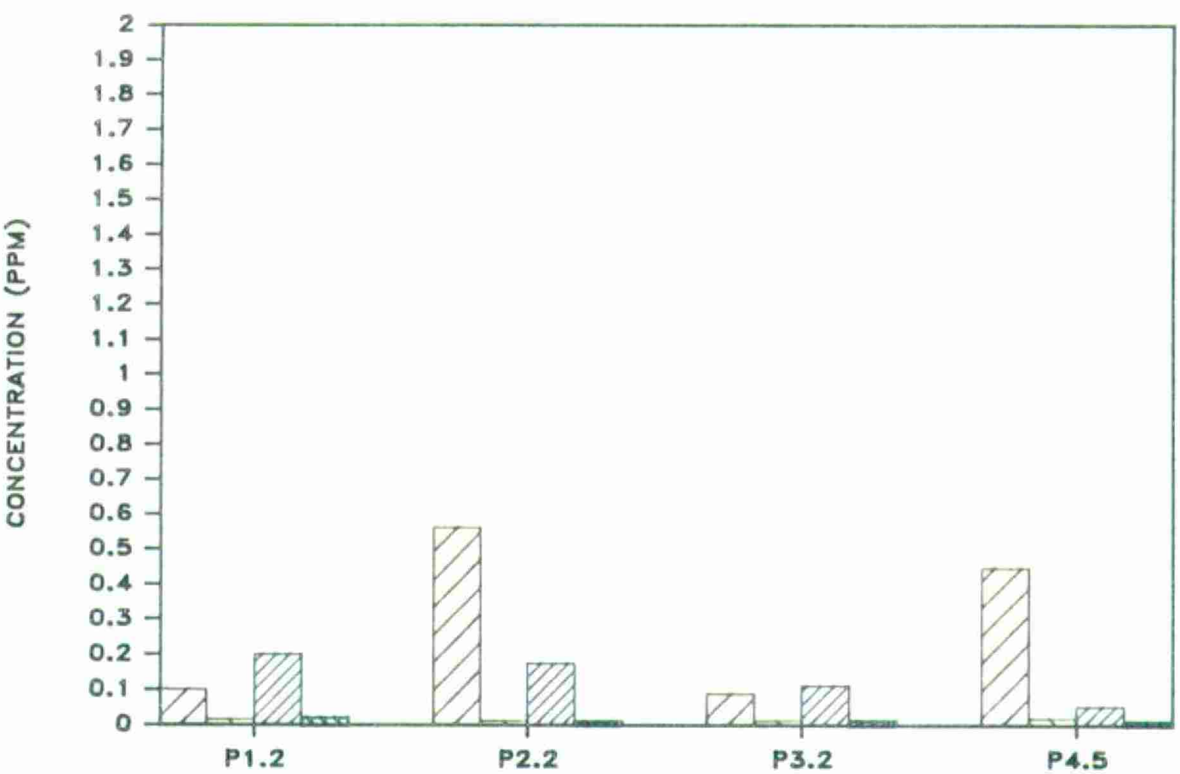




AVERAGE HEAVY METAL CONCENTRATIONS

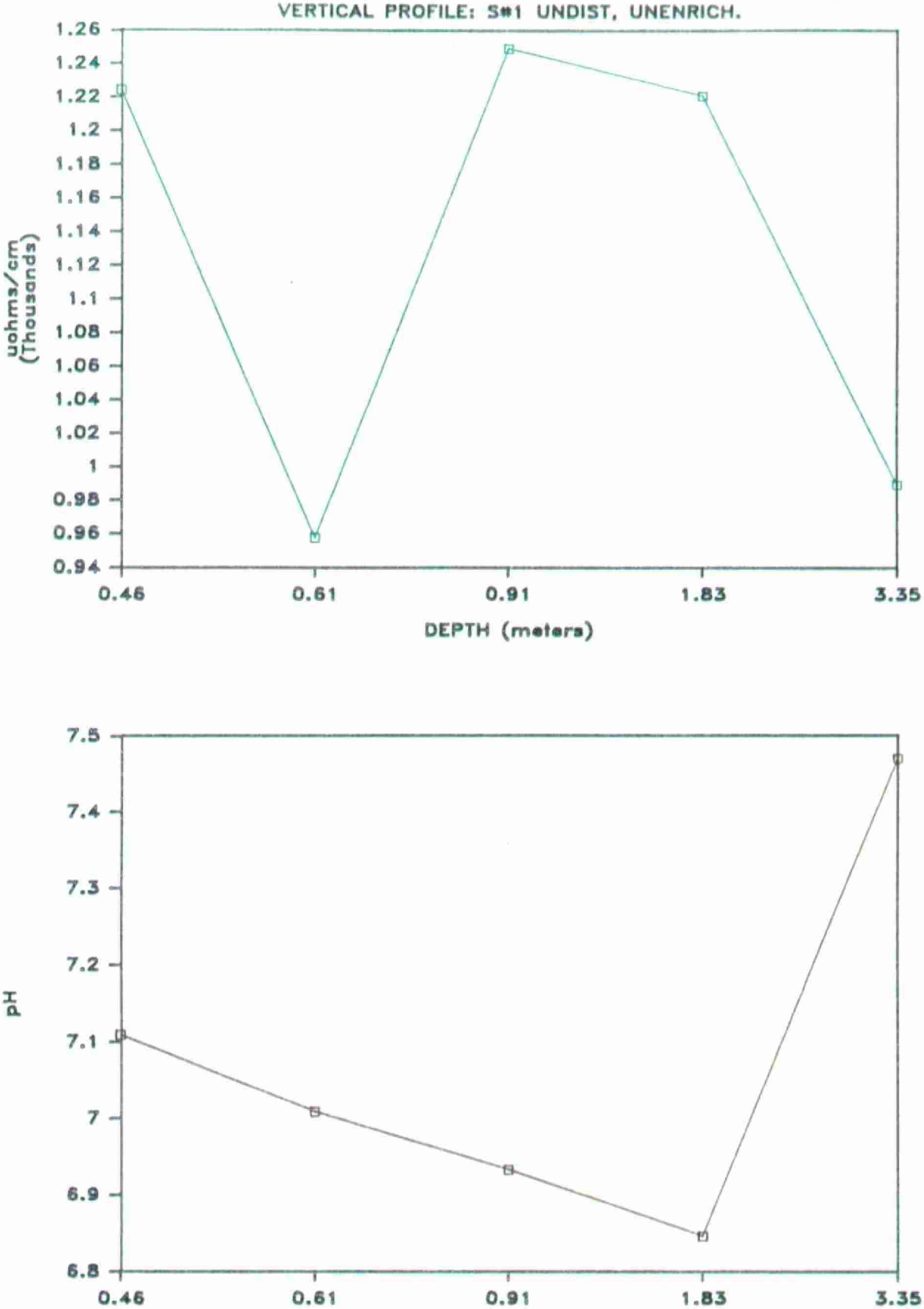
GROUNDWATER 0.9M DEPTH





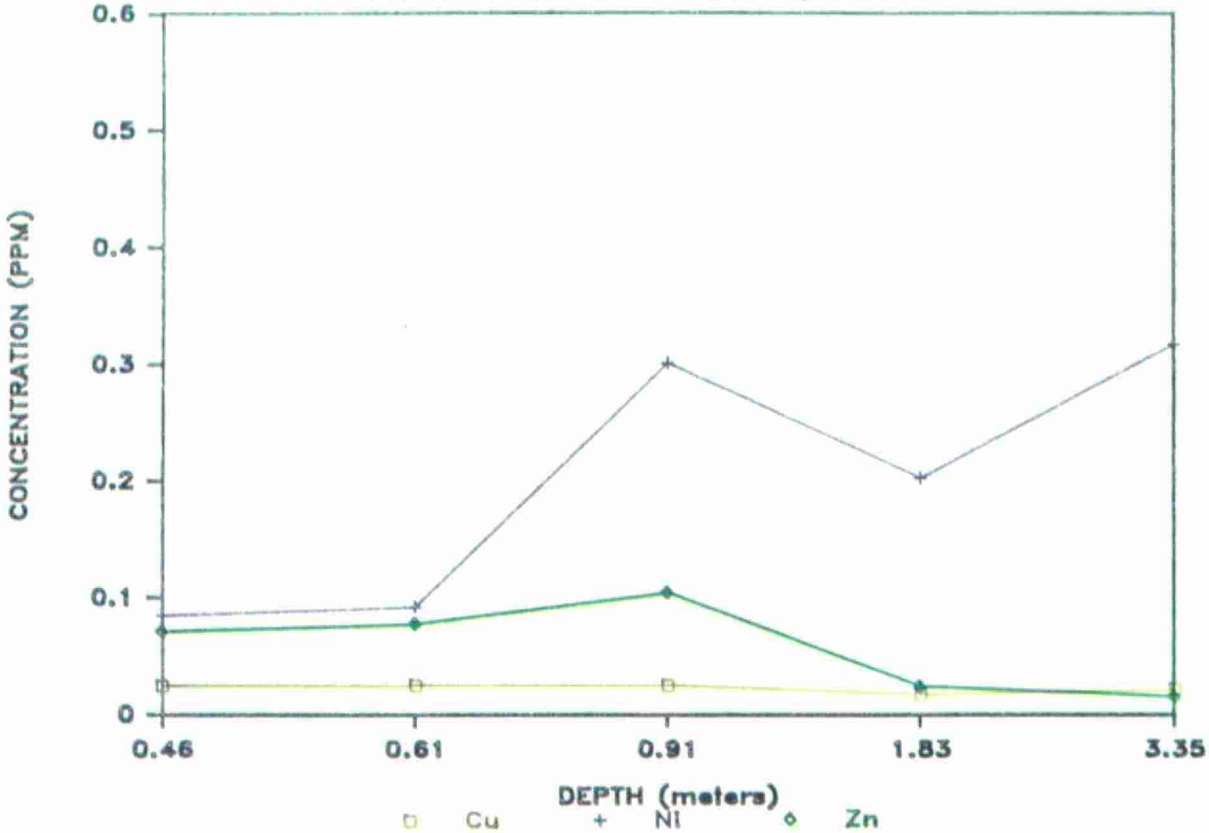
GROUNDWATER CONDUCTIVITY + pH

VERTICAL PROFILE: S#1 UNDIST, UNENRICH.

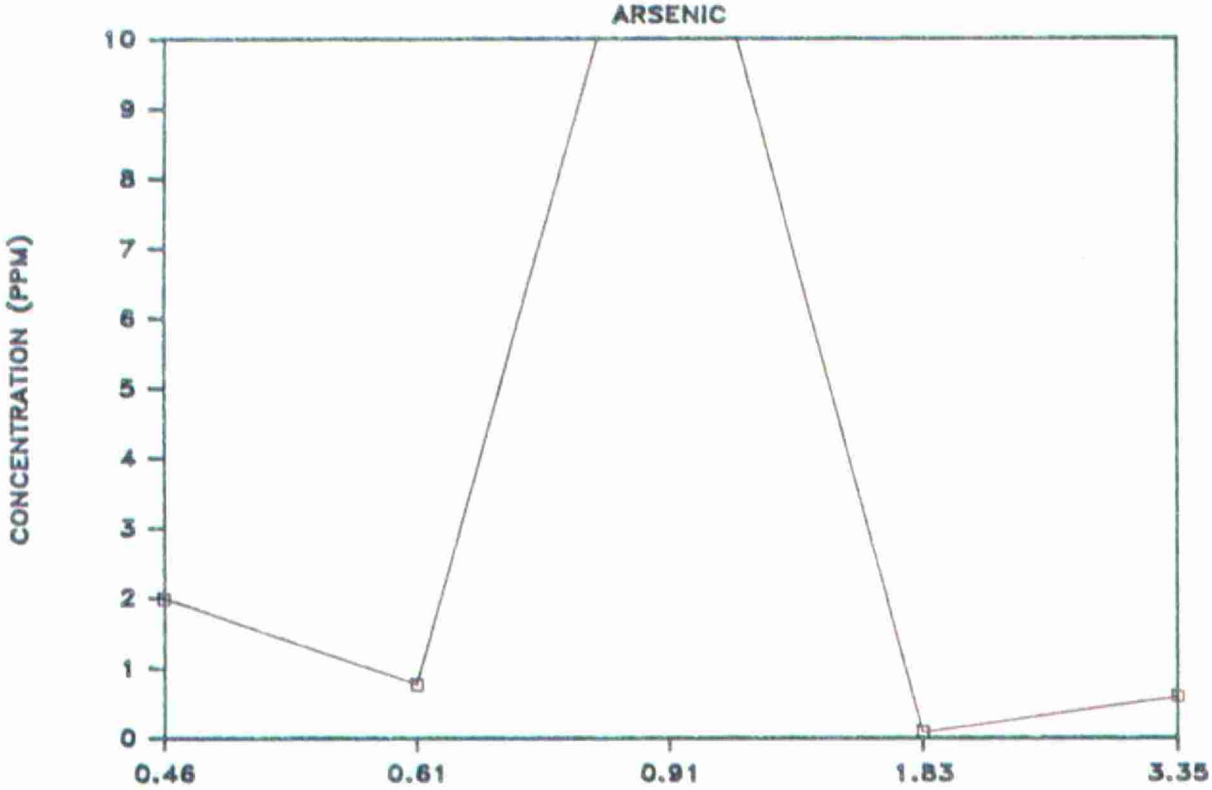


HEAVY METALS IN GROUNDWATER

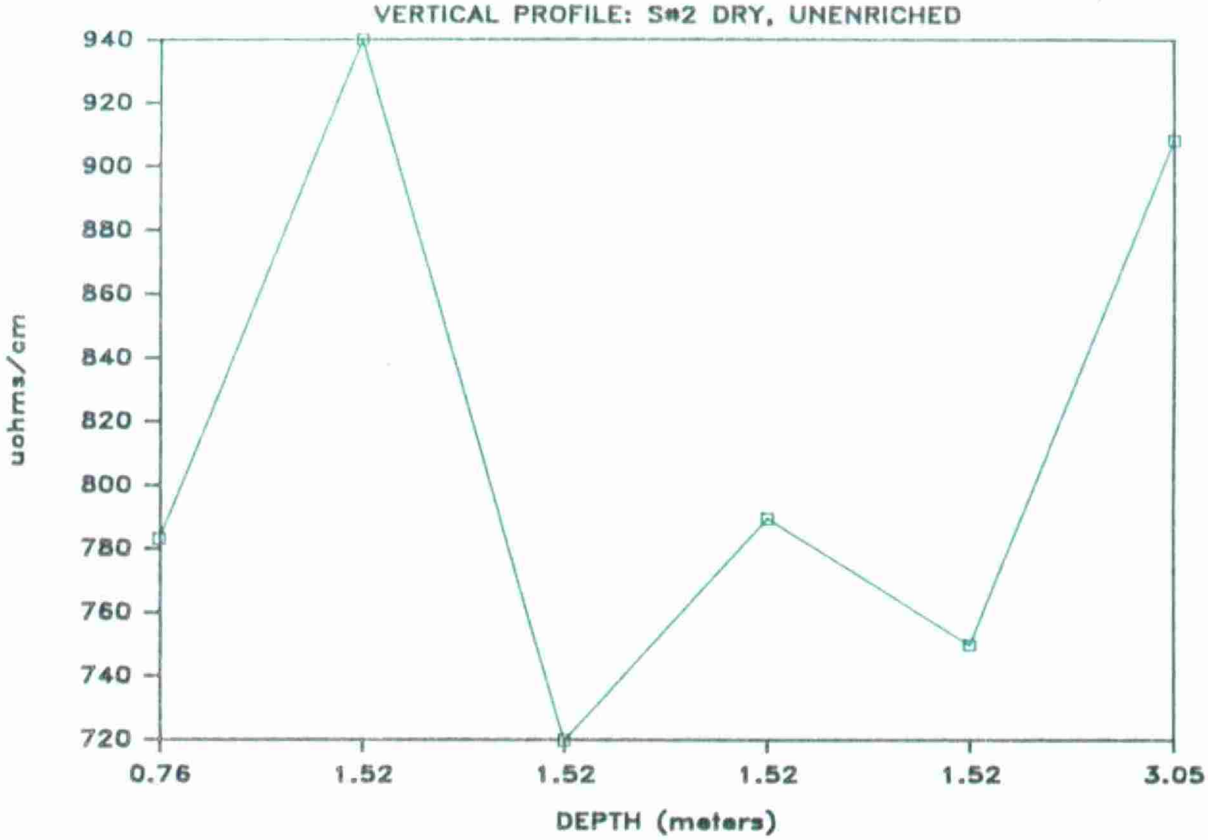
VERTICAL PROFILE: S#1 UNDIST, UNENRICH.

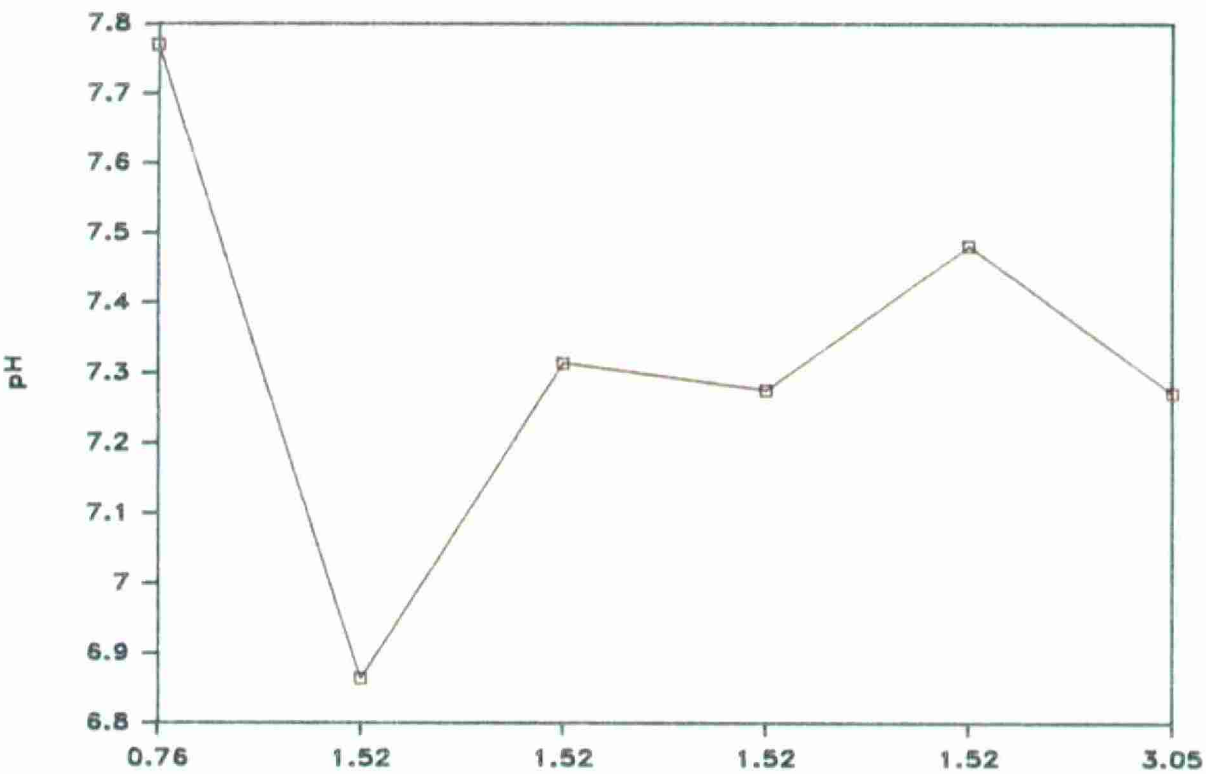


ARSENIC



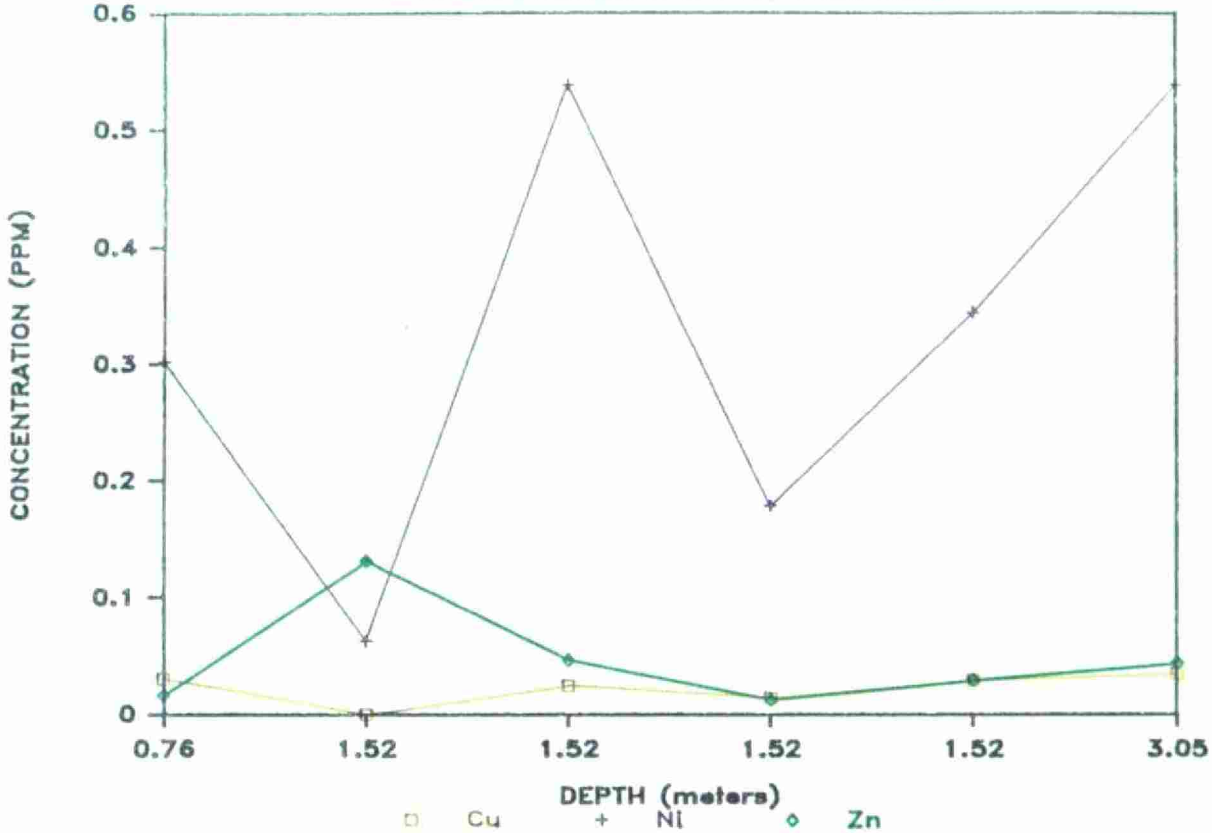
GROUNDWATER CONDUCTIVITY + pH



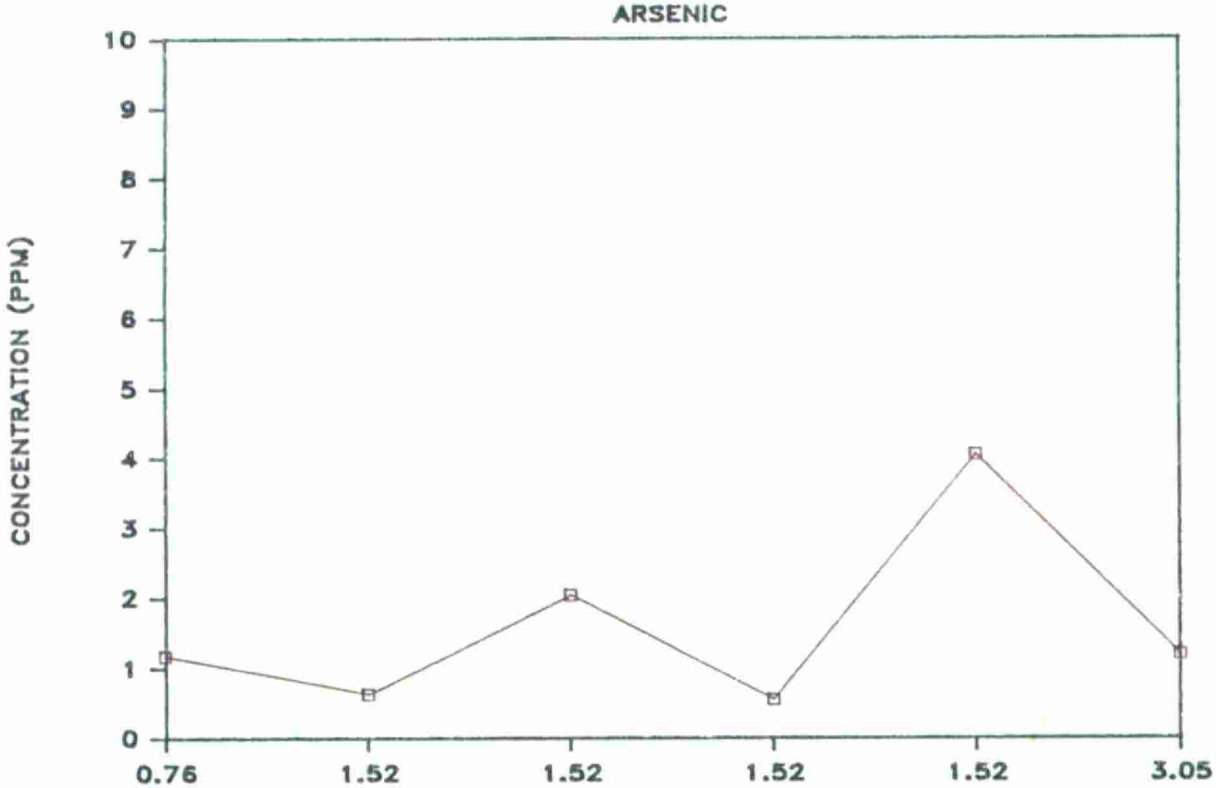


HEAVY METALS IN GROUNDWATER

VERTICAL PROFILE: S#2 DRY, UNENRICHED

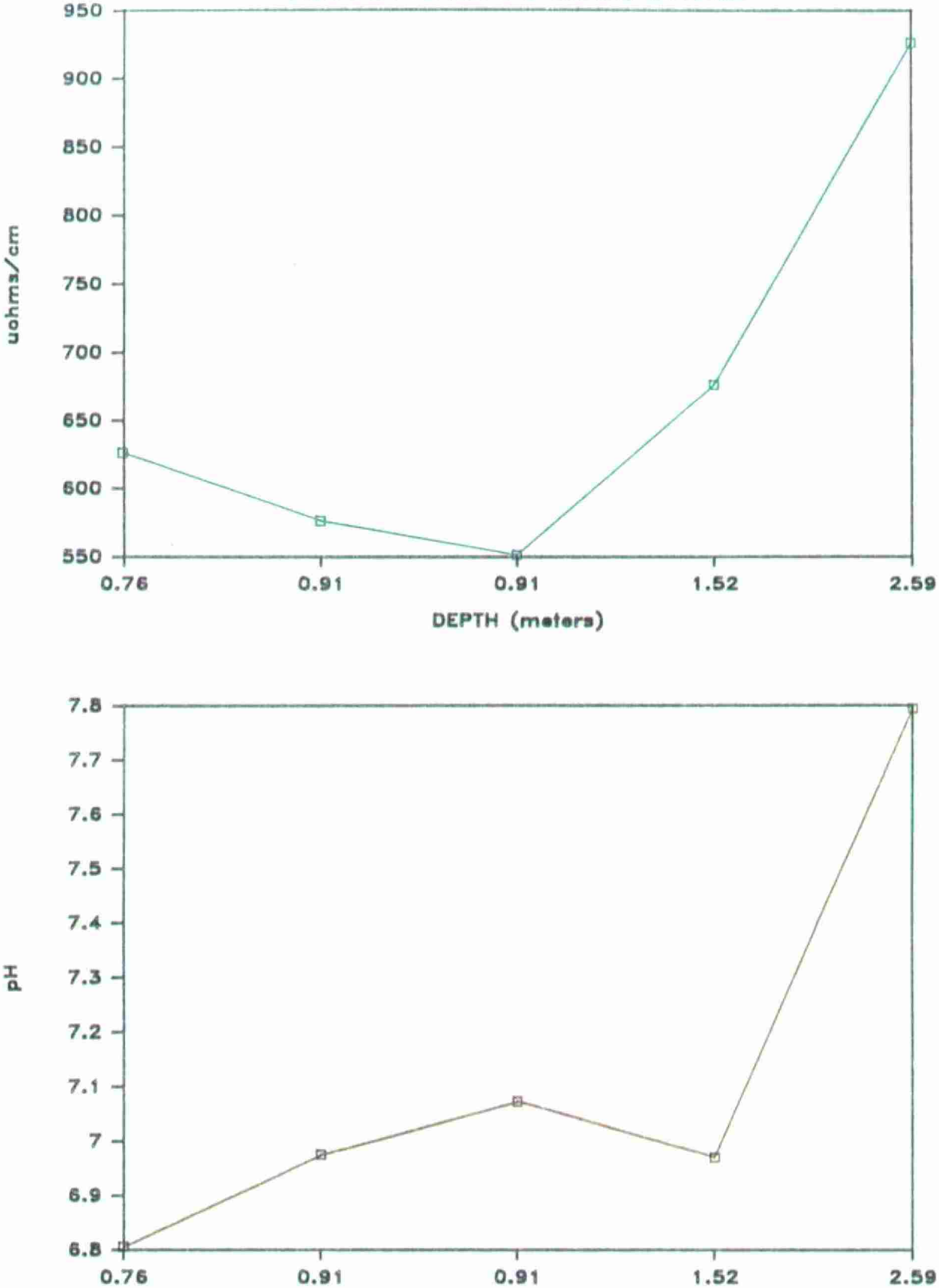


ARSENIC



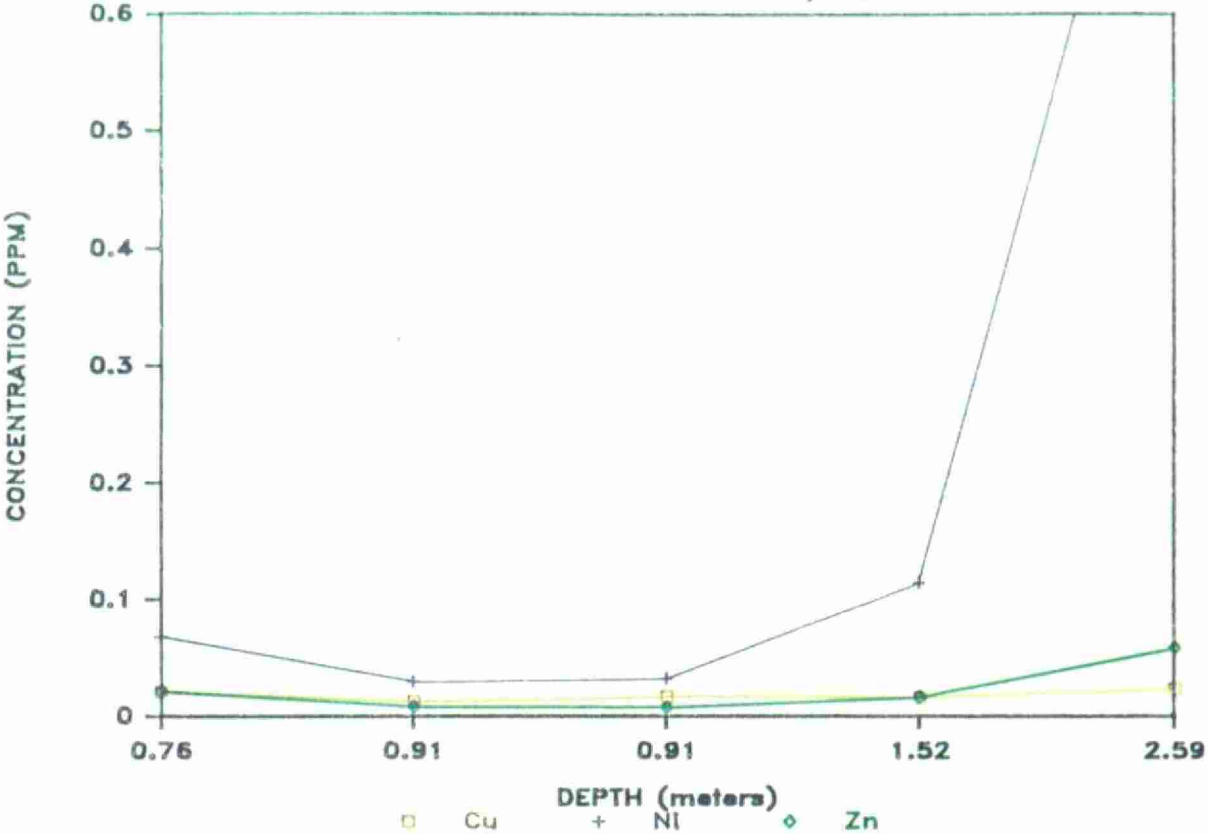
GROUNDWATER CONDUCTIVITY + pH

VERTICAL PROFILE: S#3 UNDIST, ENRICHED

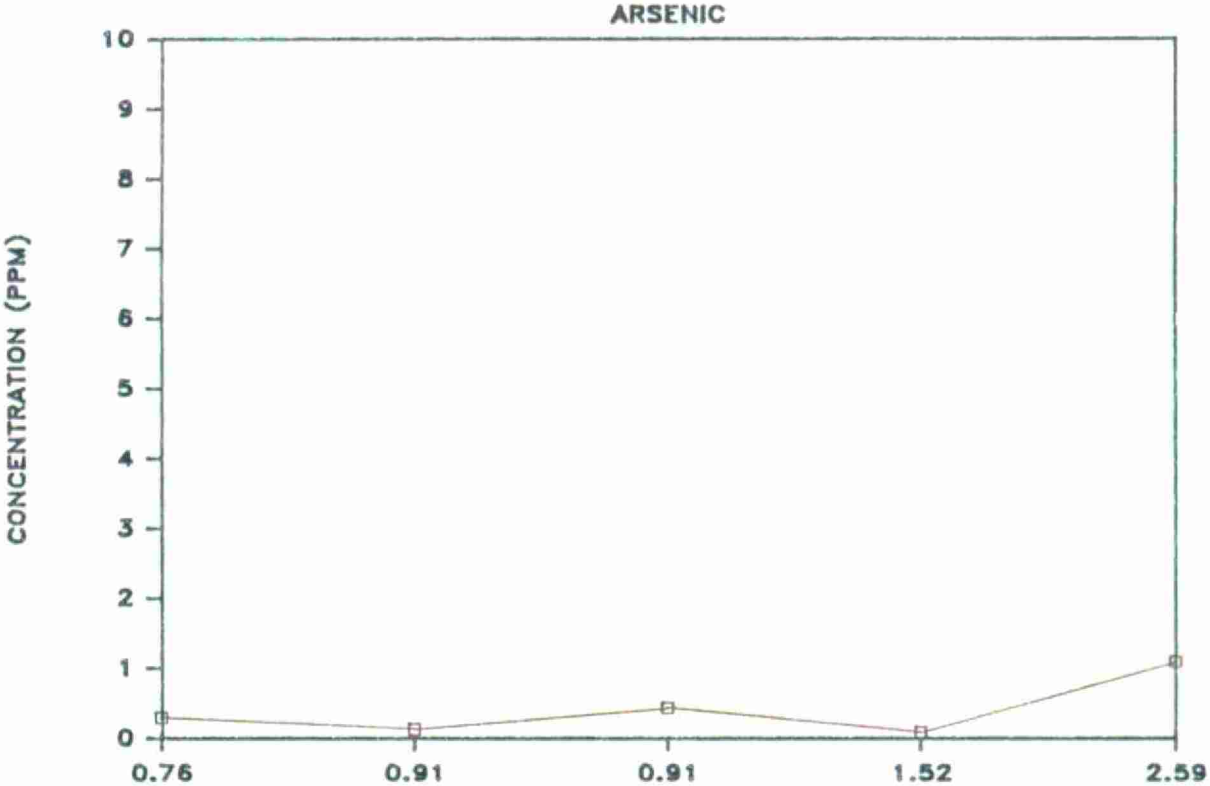


HEAVY METALS IN GROUNDWATER

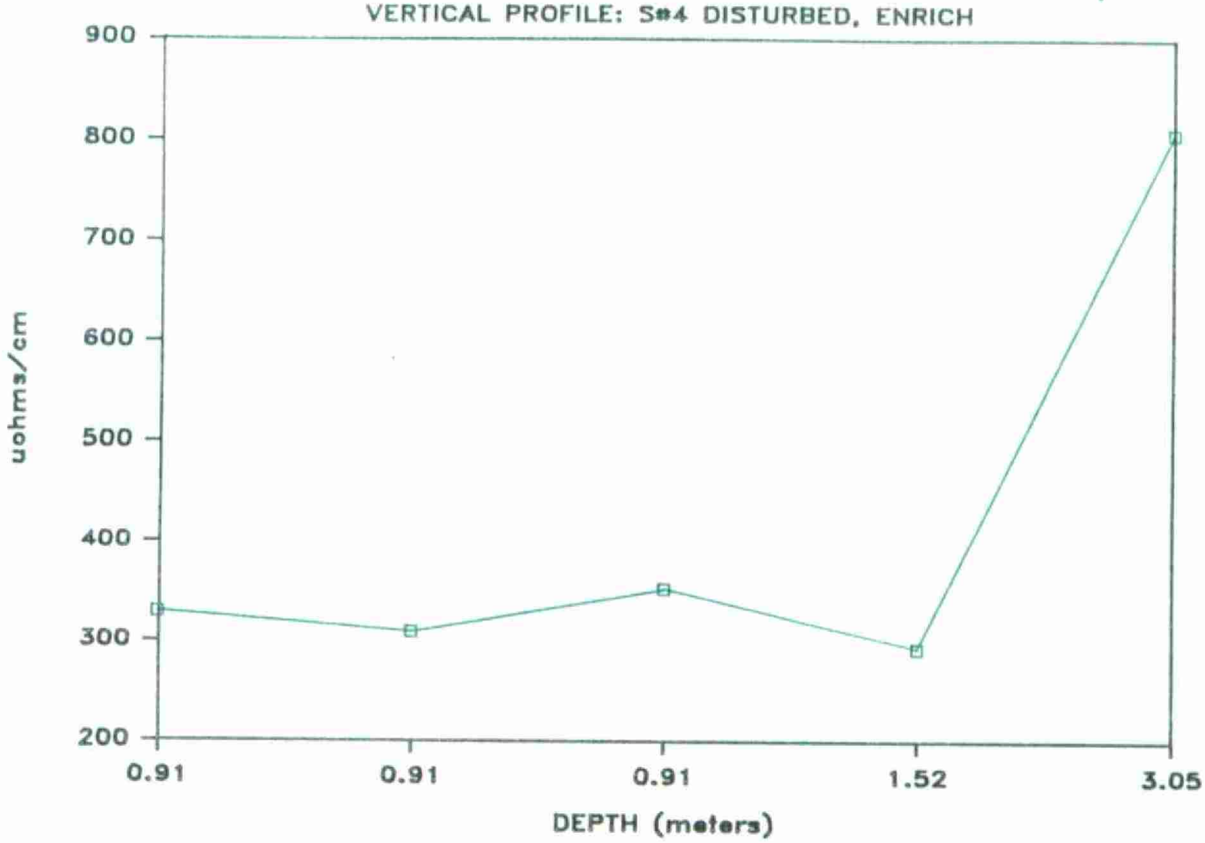
VERTICAL PROFILE: S#3 UNDIST, ENRICHED

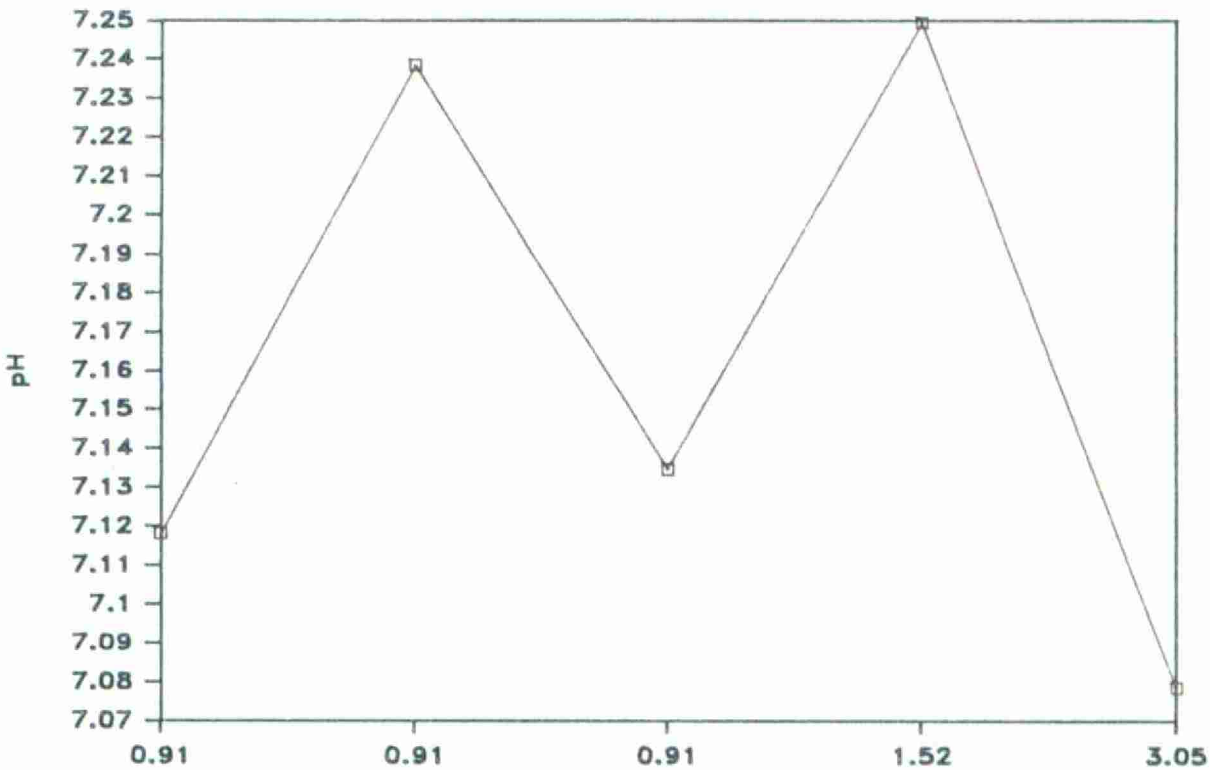


ARSENIC

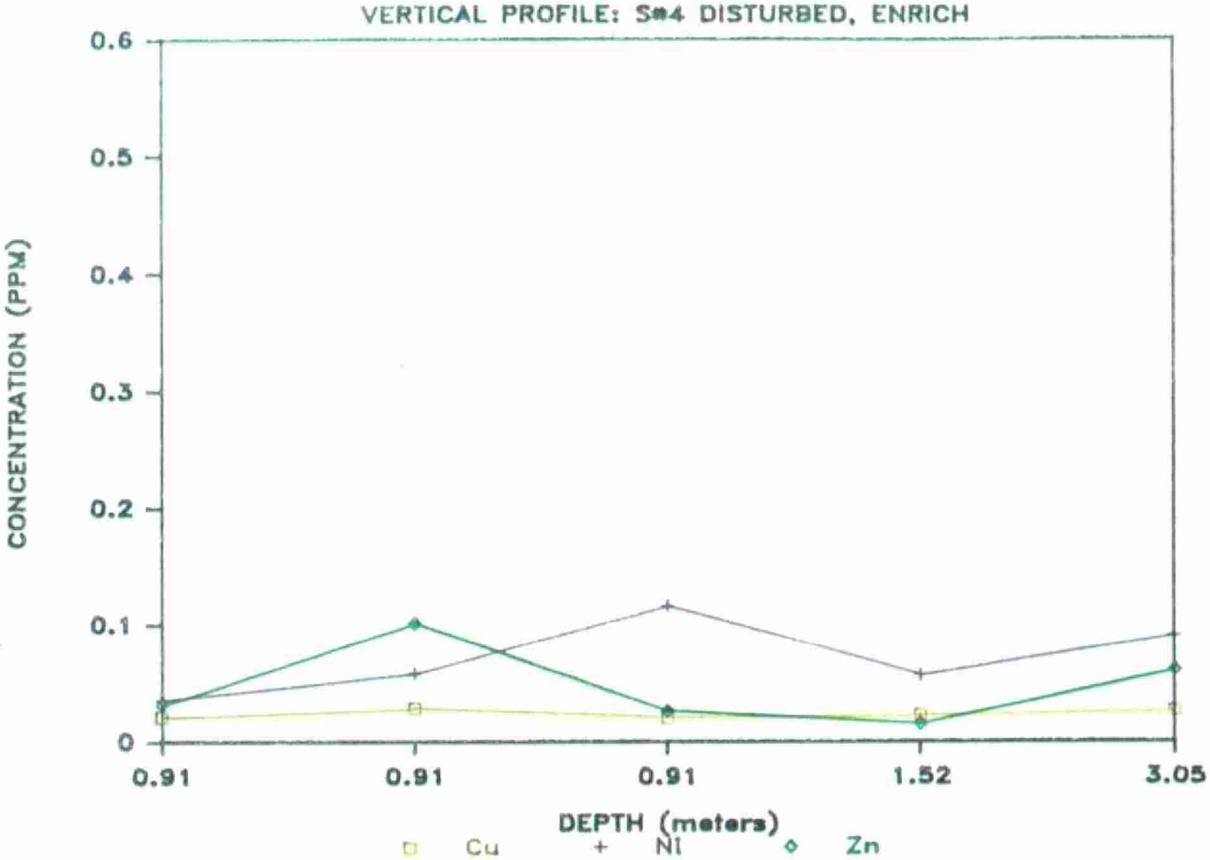


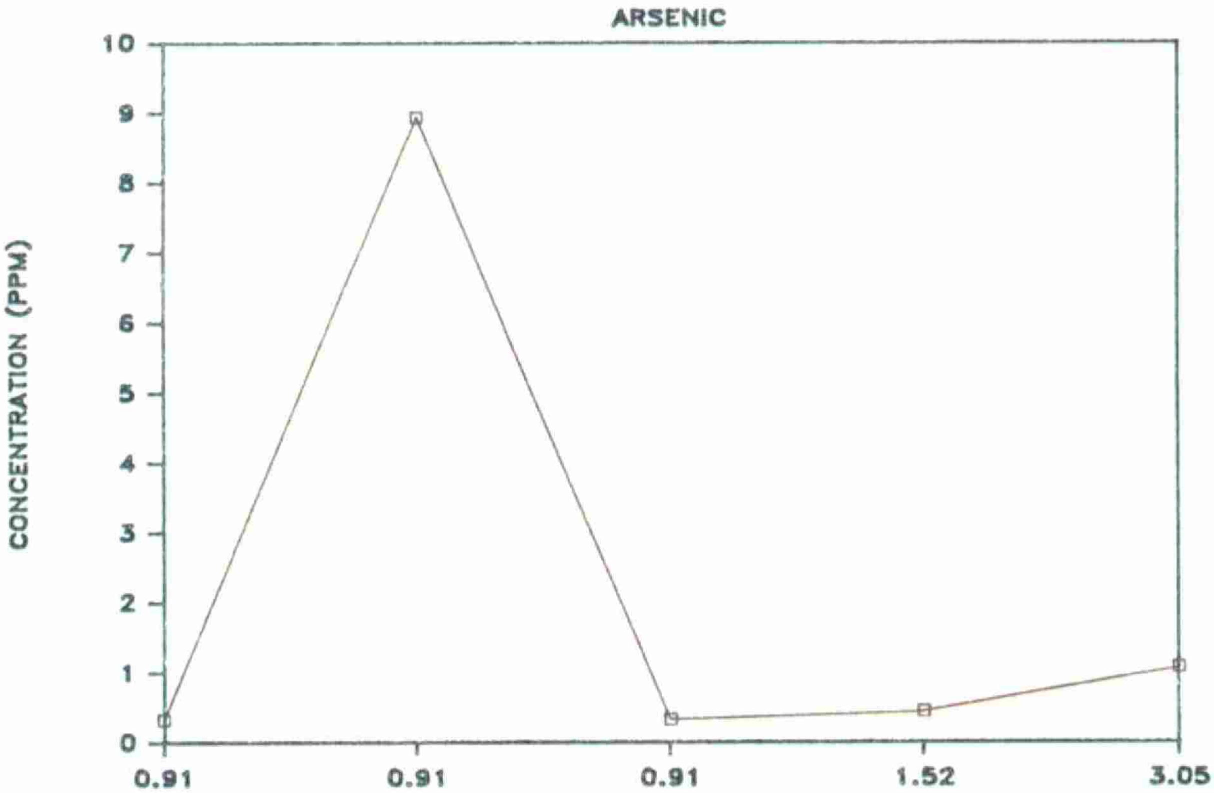
GROUNDWATER CONDUCTIVITY + pH



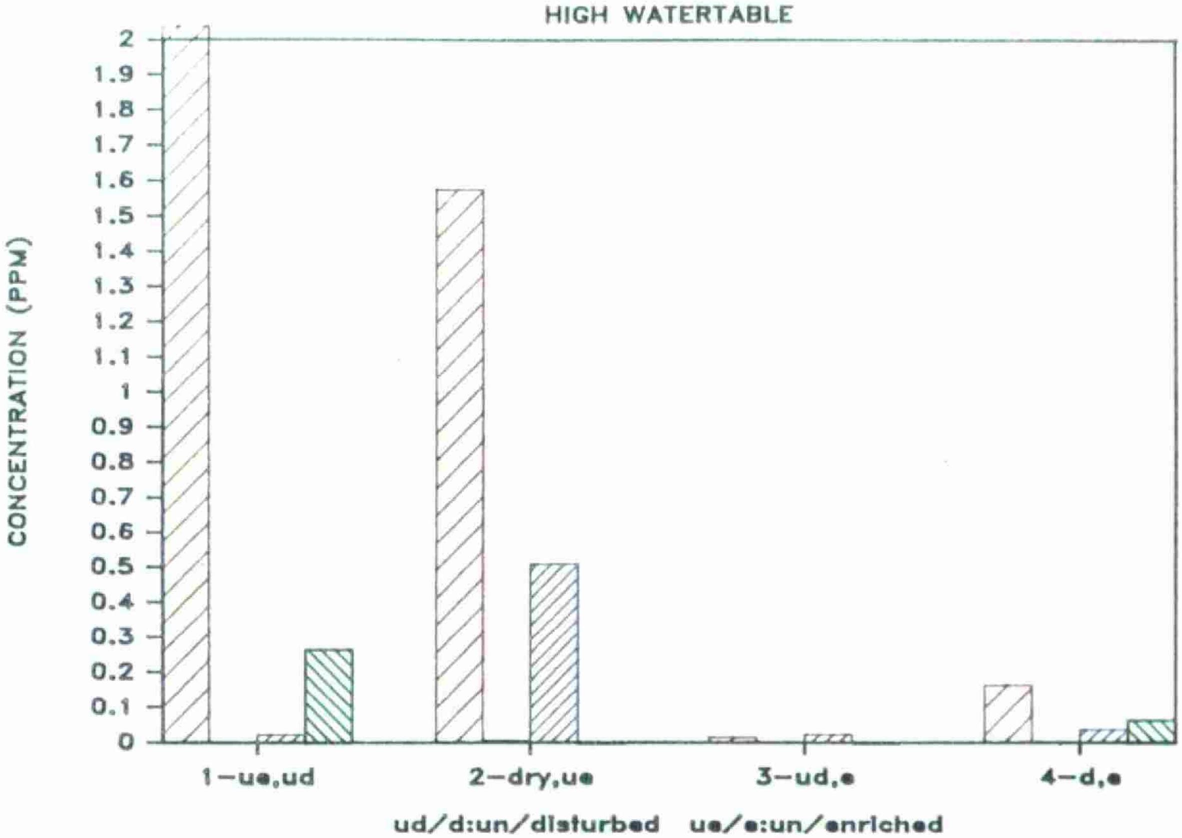


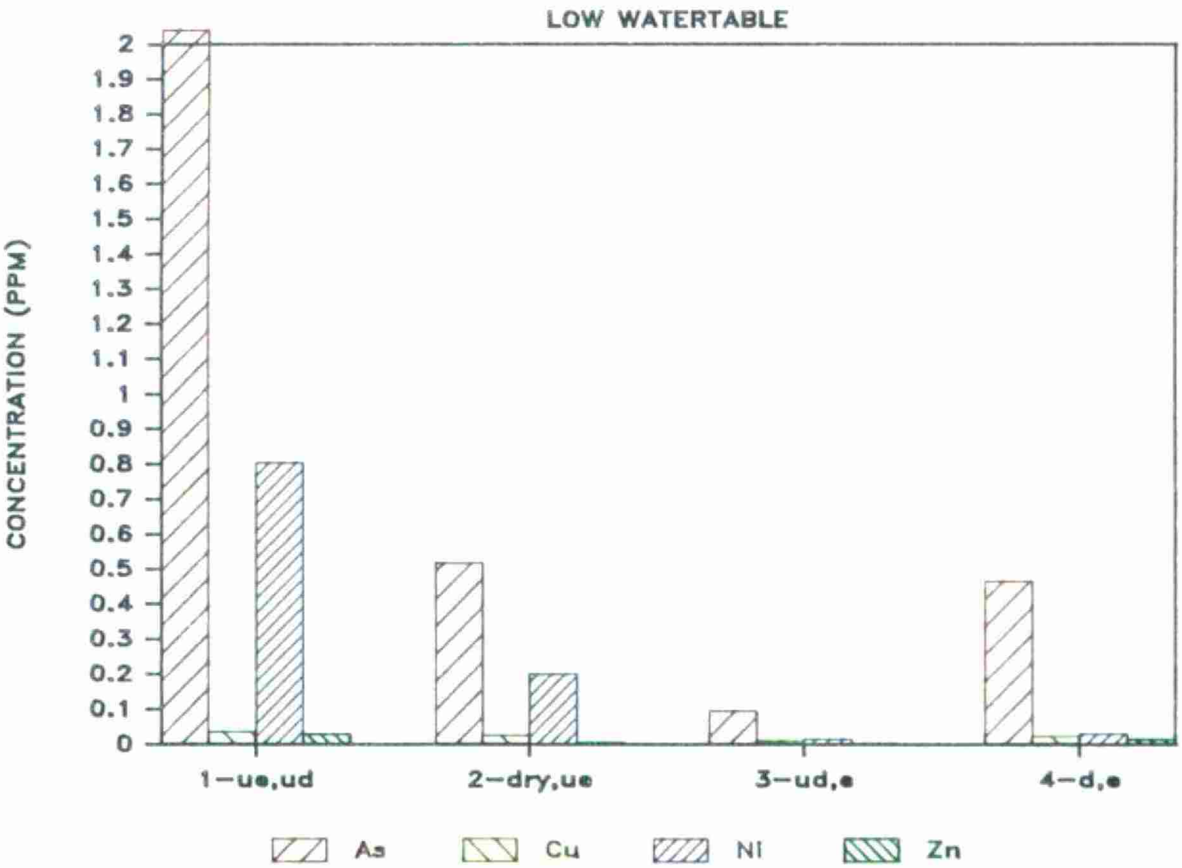
HEAVY METALS IN GROUNDWATER

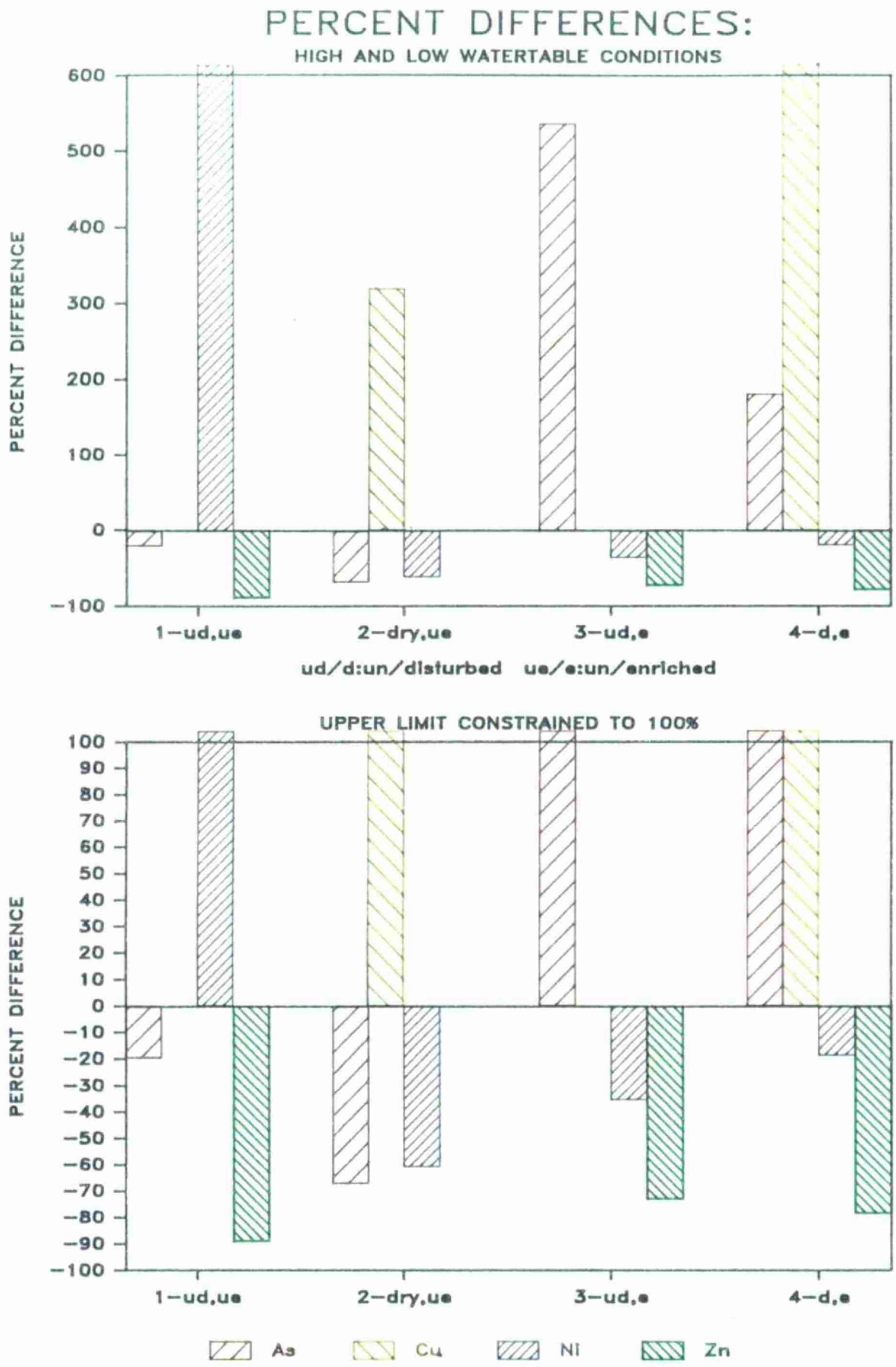




HEAVY METALS IN GROUNDWATER





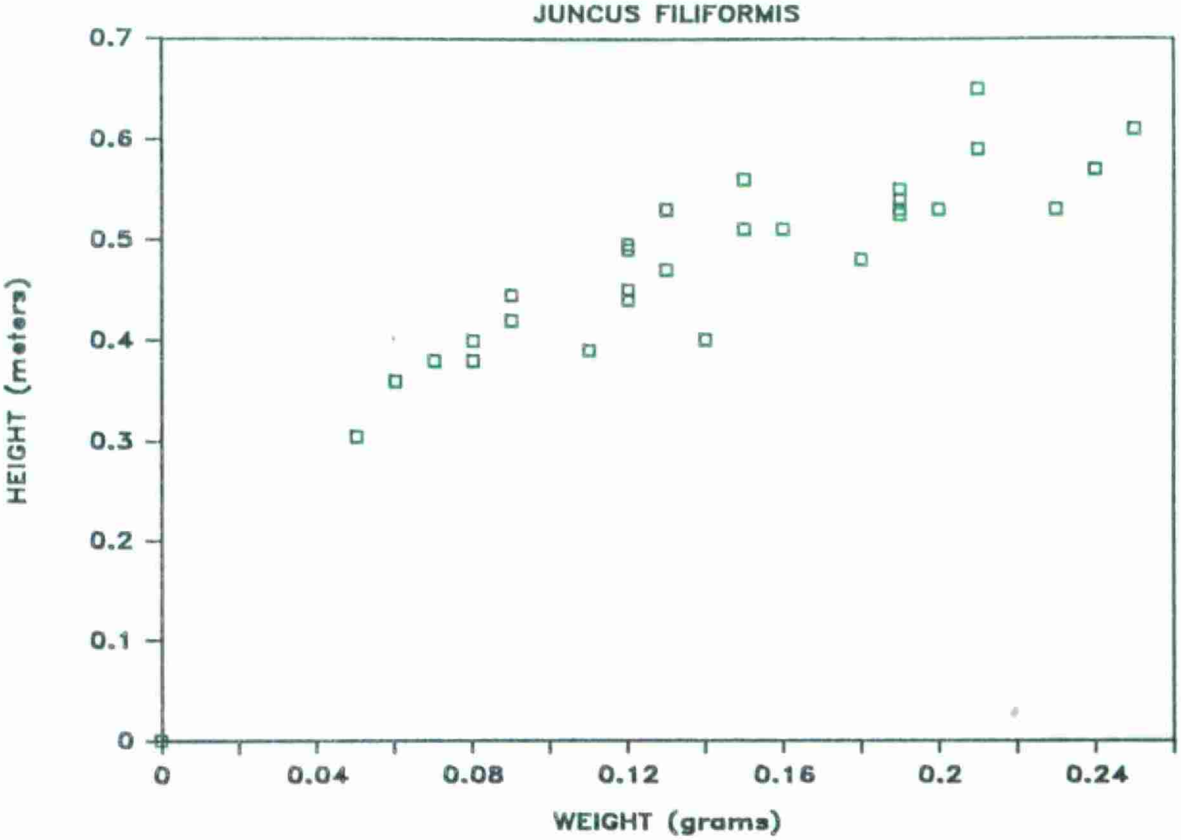


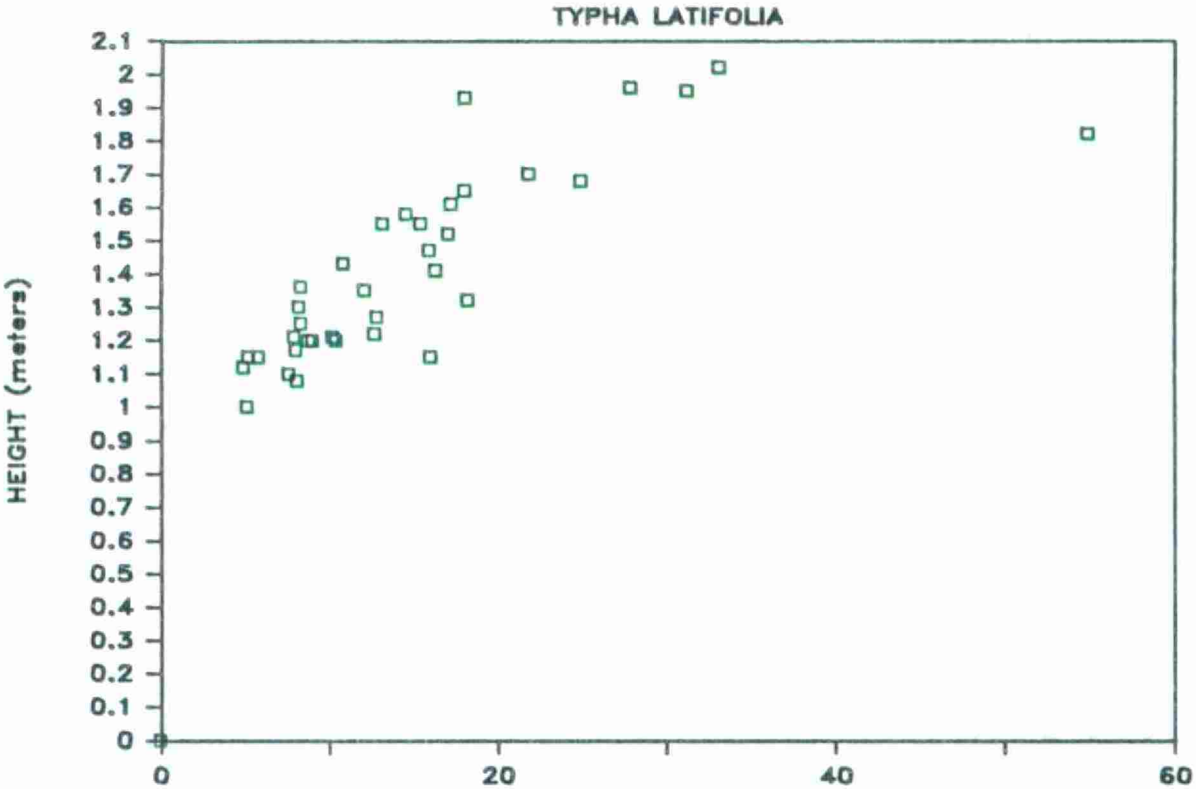
Heavy Metal Mobilization
and Bioavailability
Cobalt Mine Tailings

J E Hanna
Associates Inc.

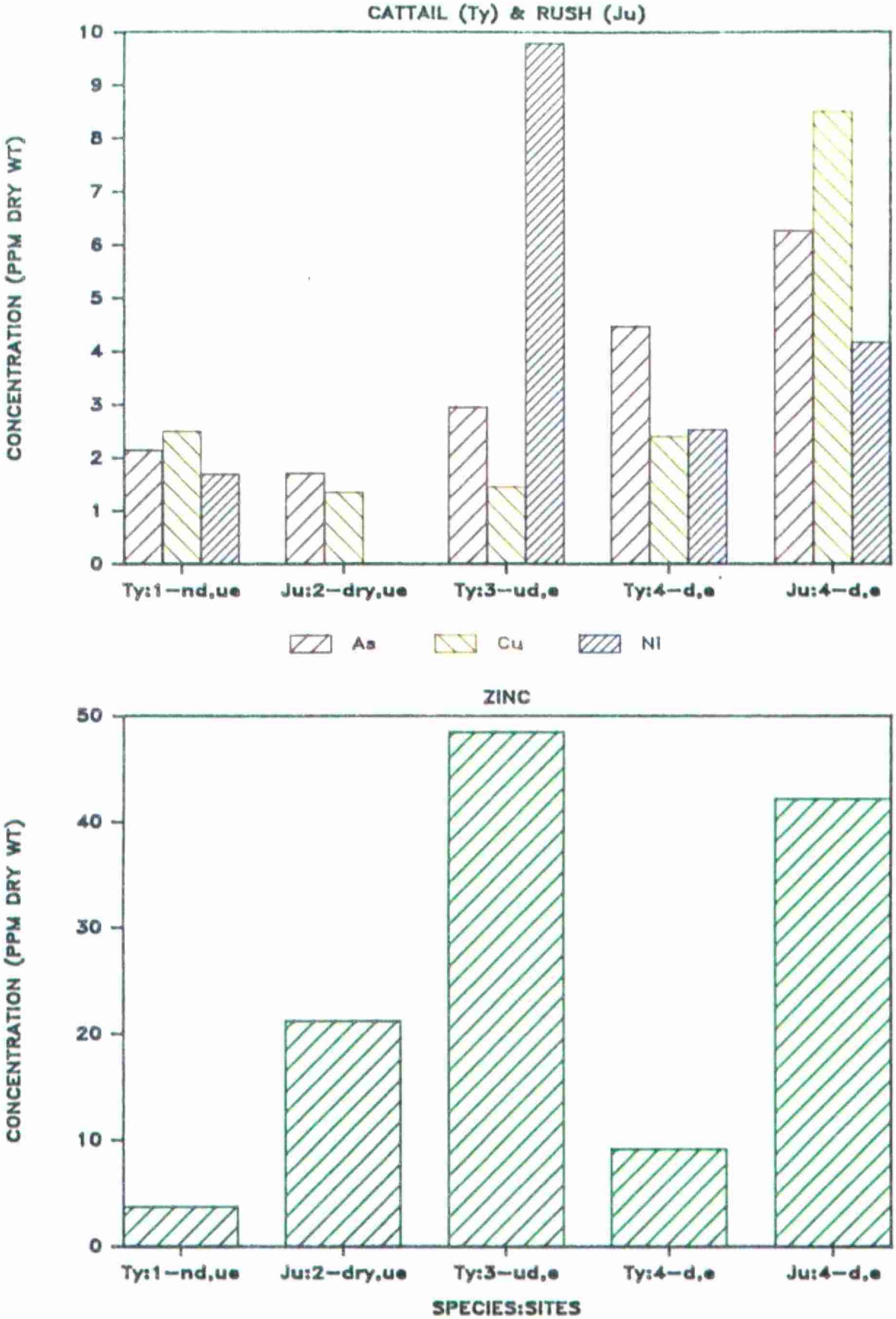
Fig. A - 46

HEIGHT/WEIGHT RELATIONSHIPS

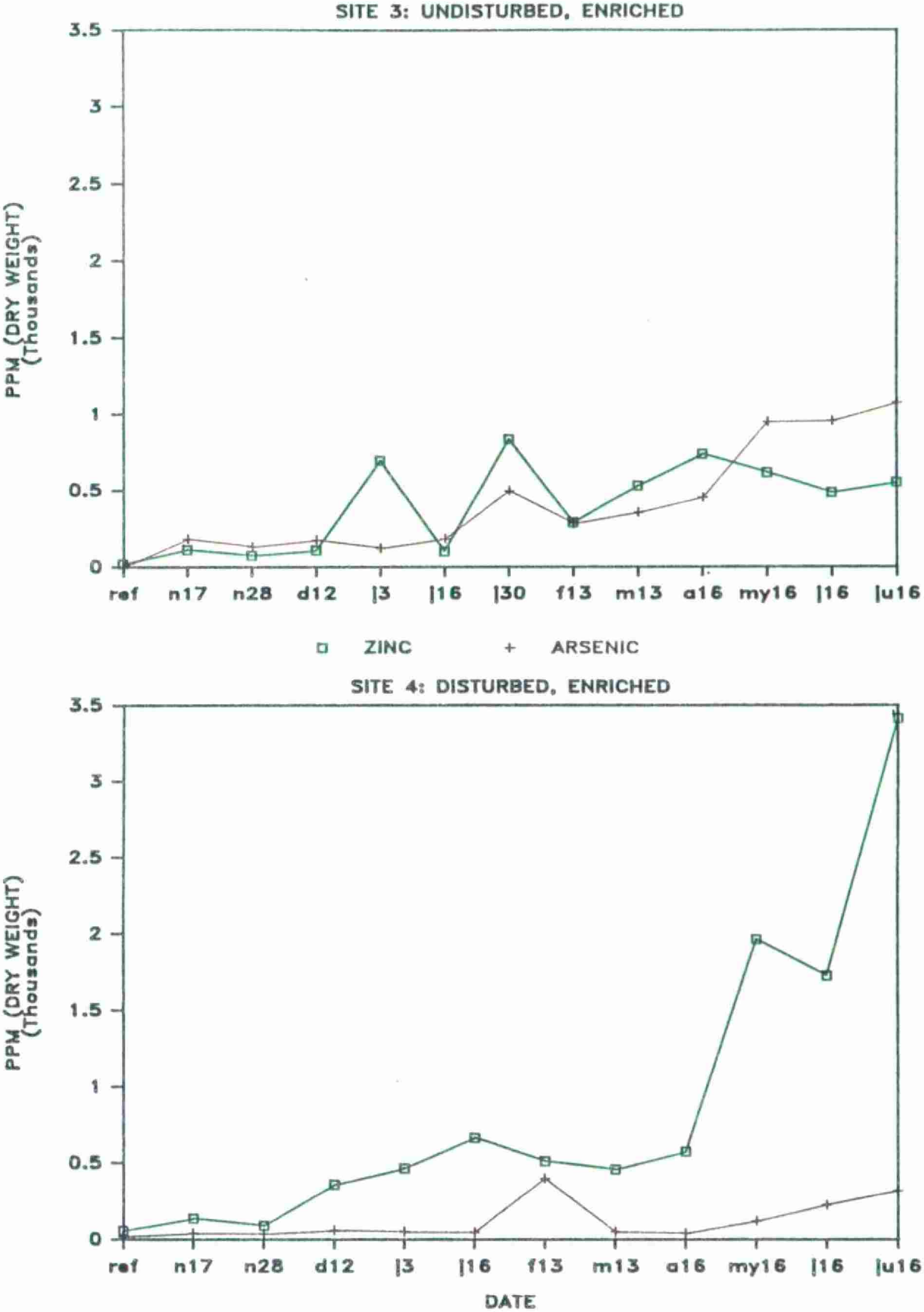




NATIVE VEGETATION METAL BURDENS

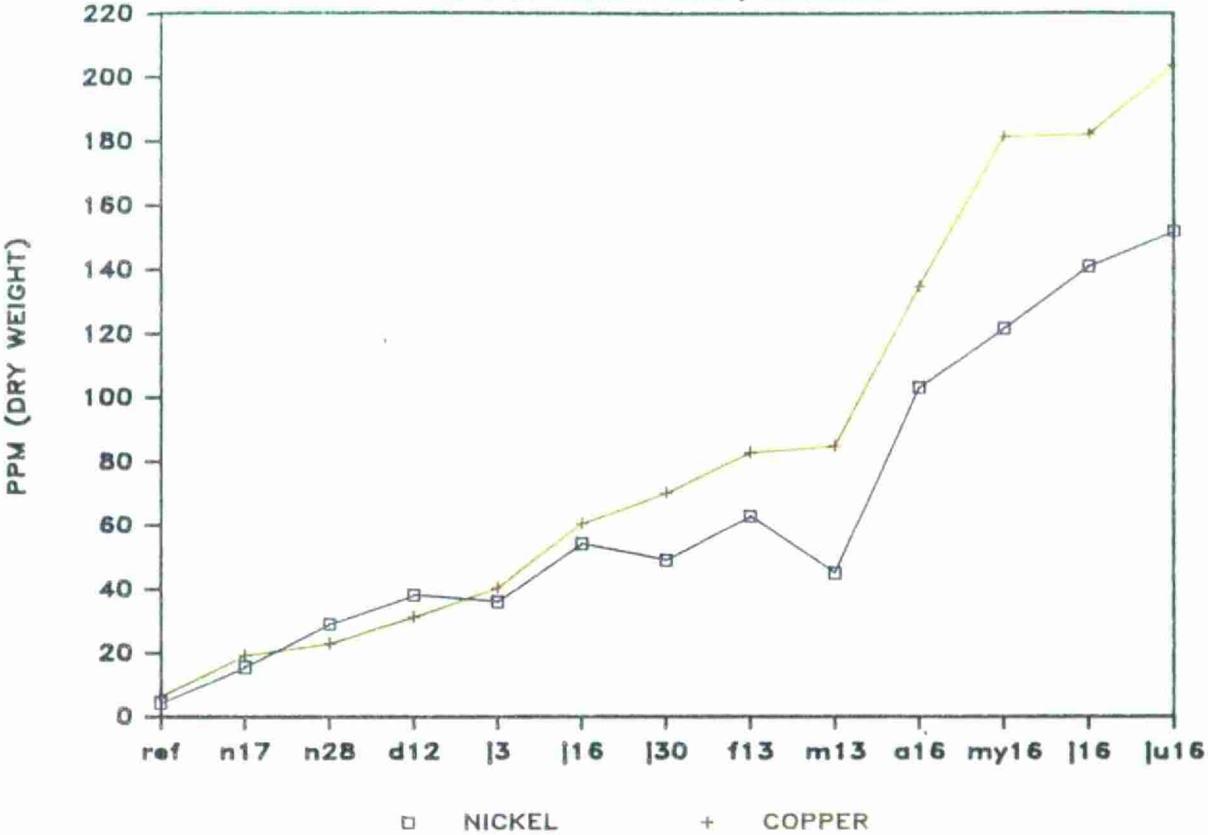


LITTER DECOMPOSITION EXPERIMENT

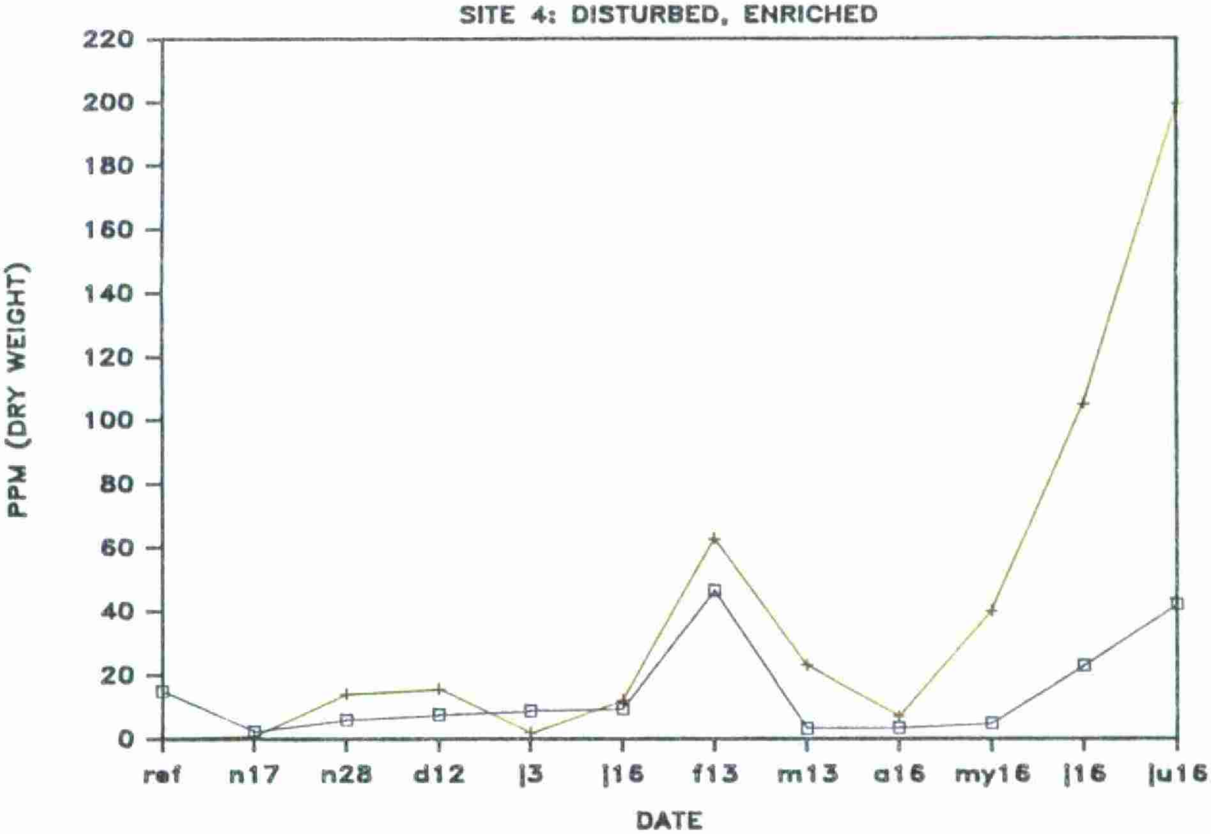


LITTER DECOMPOSITION EXPERIMENT

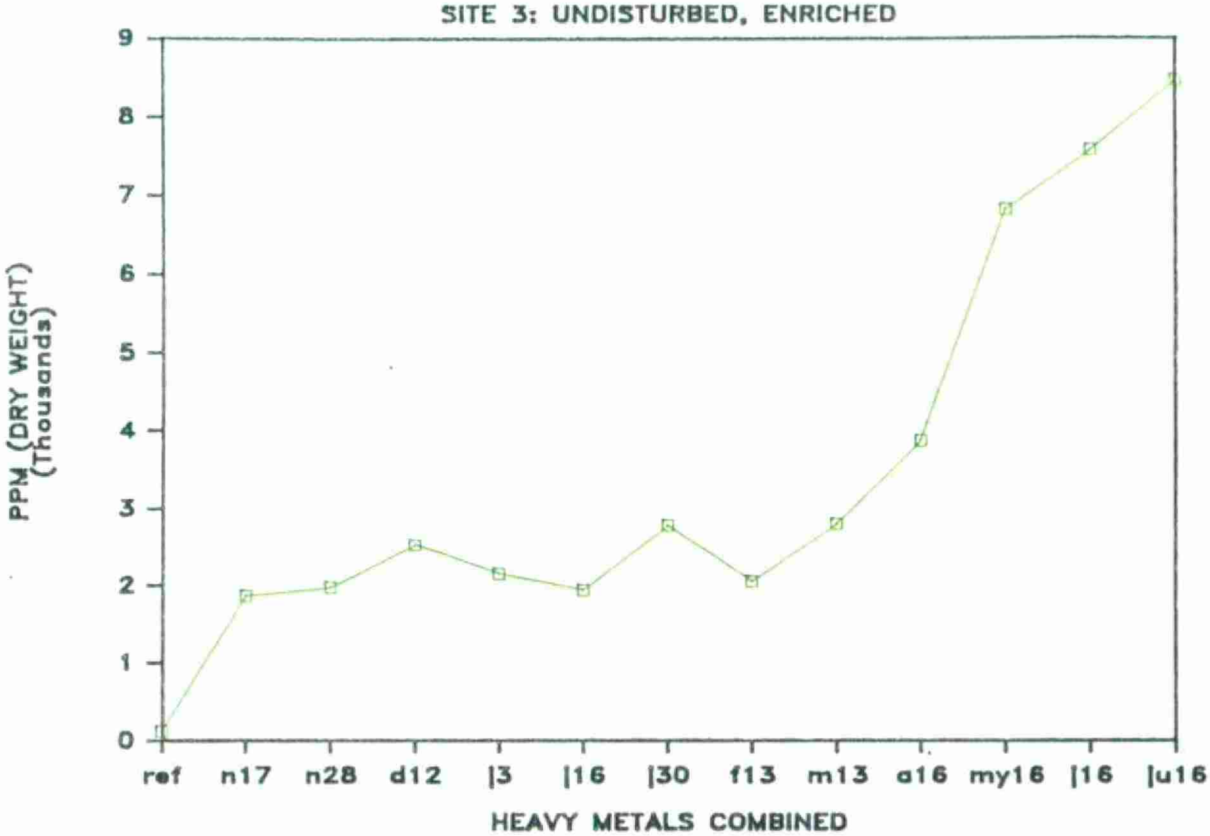
SITE 3: UNDISTURBED, ENRICHED

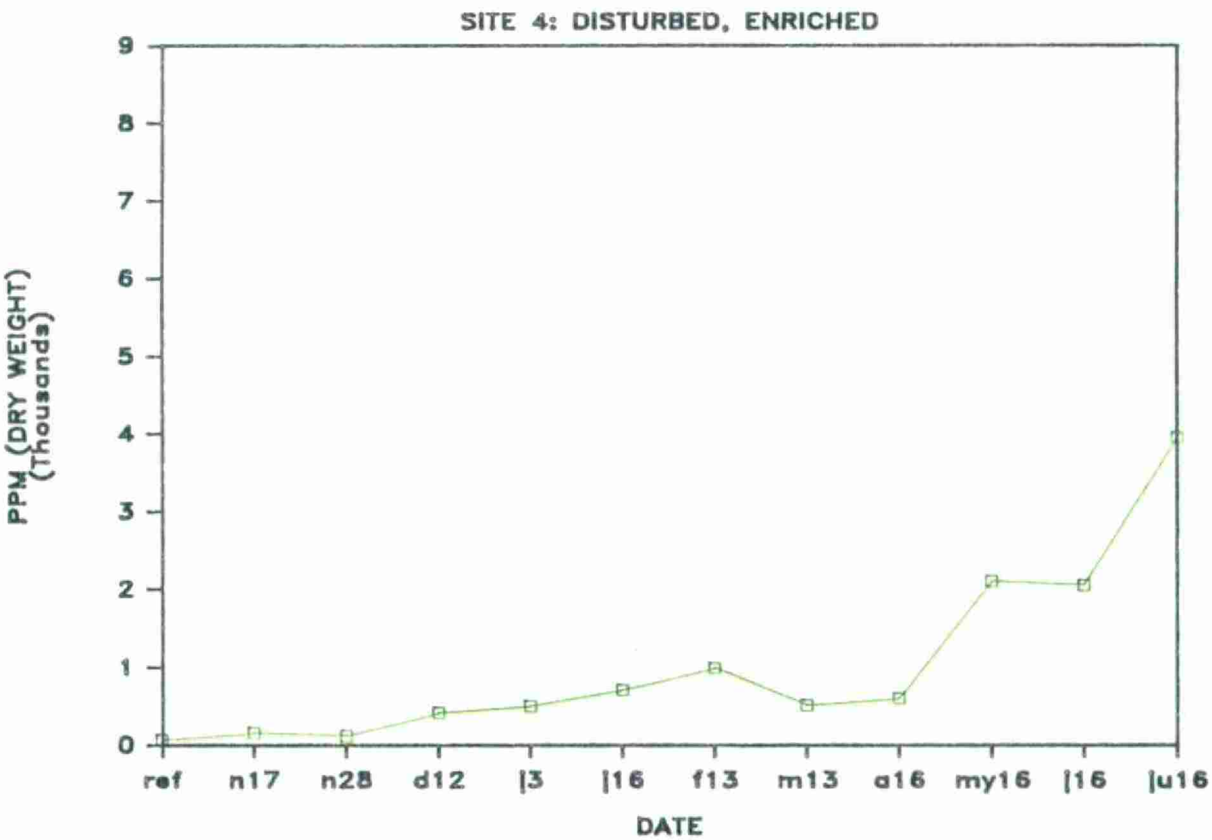


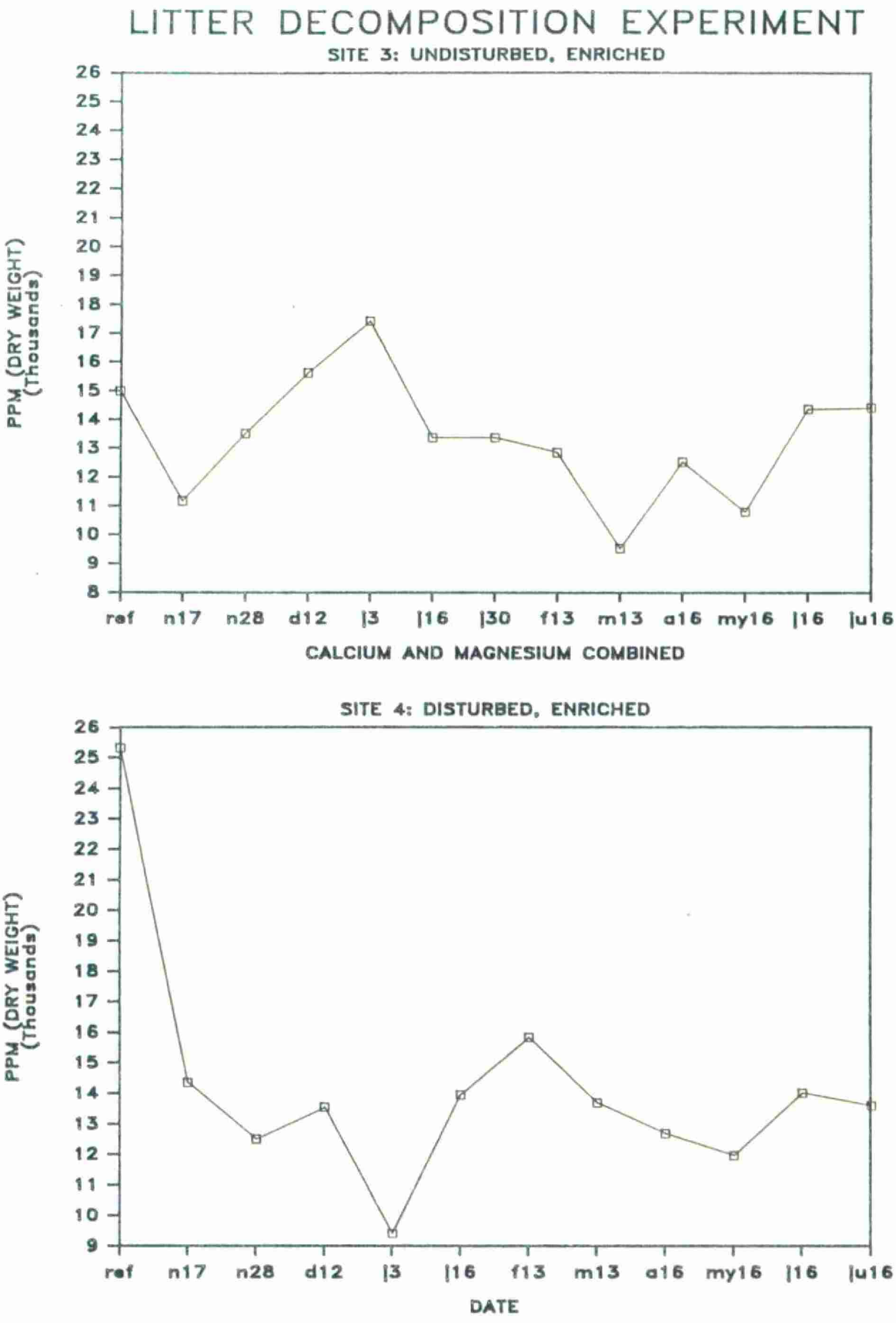
SITE 4: DISTURBED, ENRICHED



LITTER DECOMPOSITION EXPERIMENT



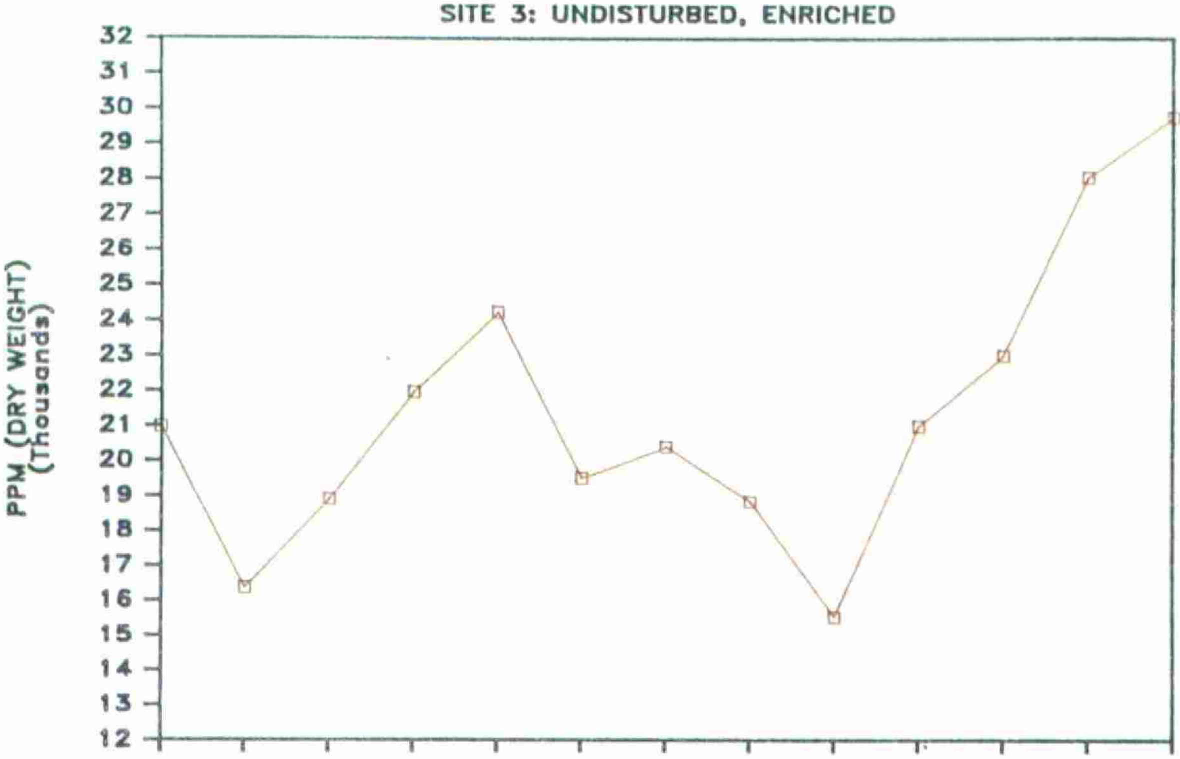




LITTER DECOMPOSITION EXPERIMENT
SITE 3: UNDISTURBED, ENRICHED
PPM (DRY WEIGHT) (Thousands)
26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8
ref n17 n28 d12 j3 j16 j30 f13 m13 a16 my16 j16 ju16
CALCIUM AND MAGNESIUM COMBINED
SITE 4: DISTURBED, ENRICHED
PPM (DRY WEIGHT) (Thousands)
26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9
ref n17 n28 d12 j3 j16 f13 m13 a16 my16 j16 ju16
DATE

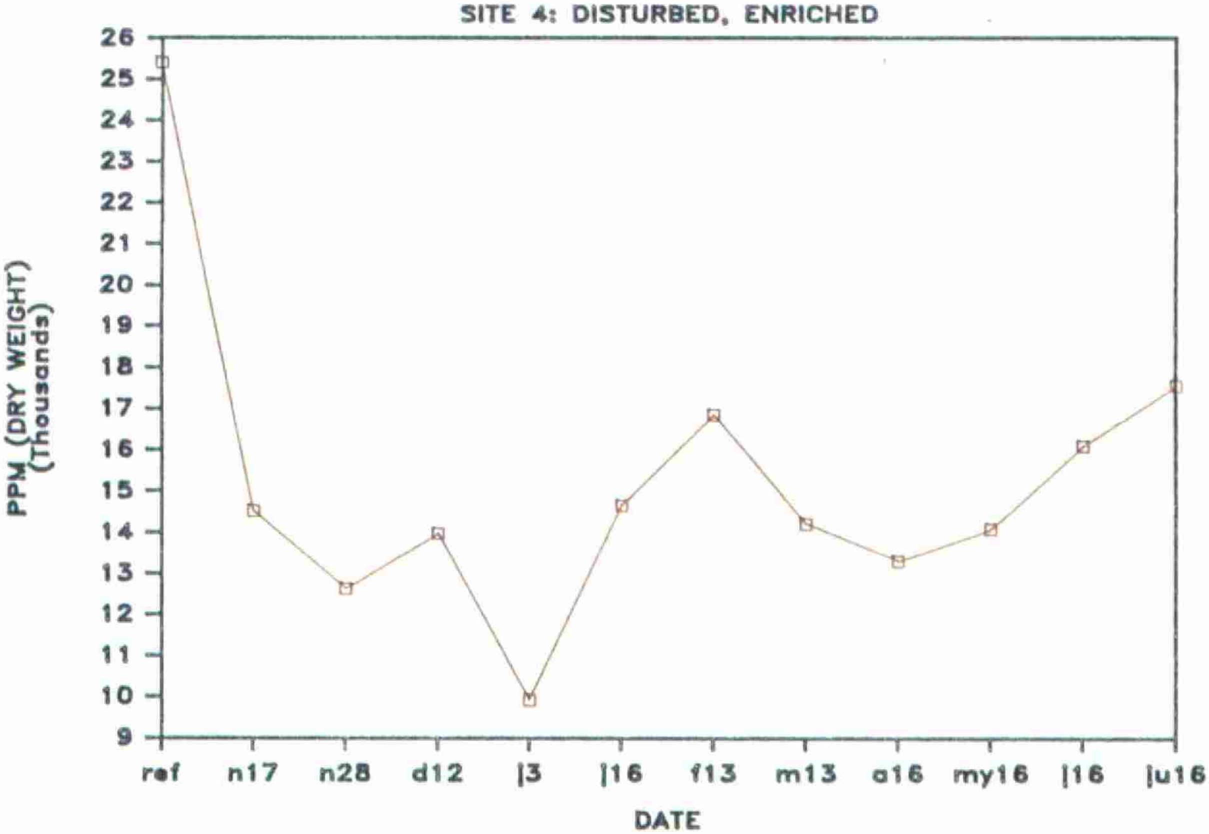
LITTER DECOMPOSITION EXPERIMENT

SITE 3: UNDISTURBED, ENRICHED

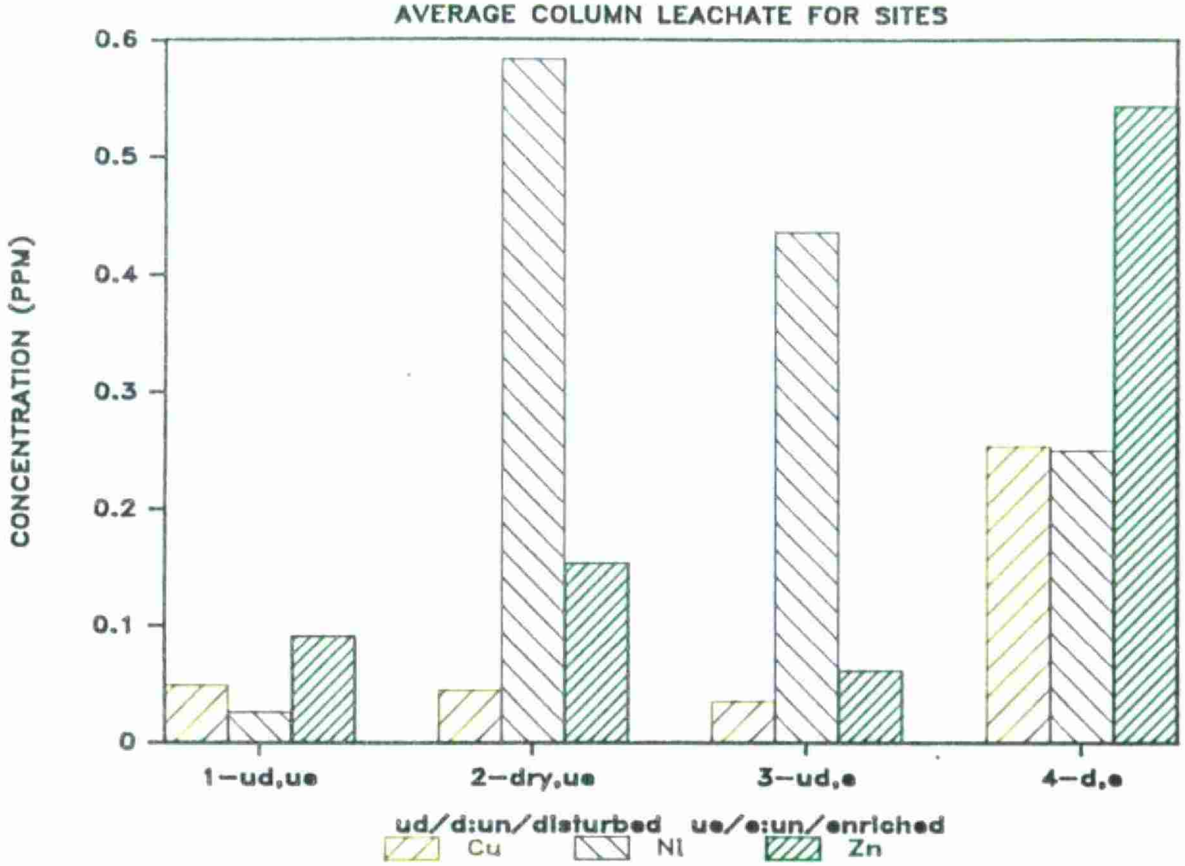


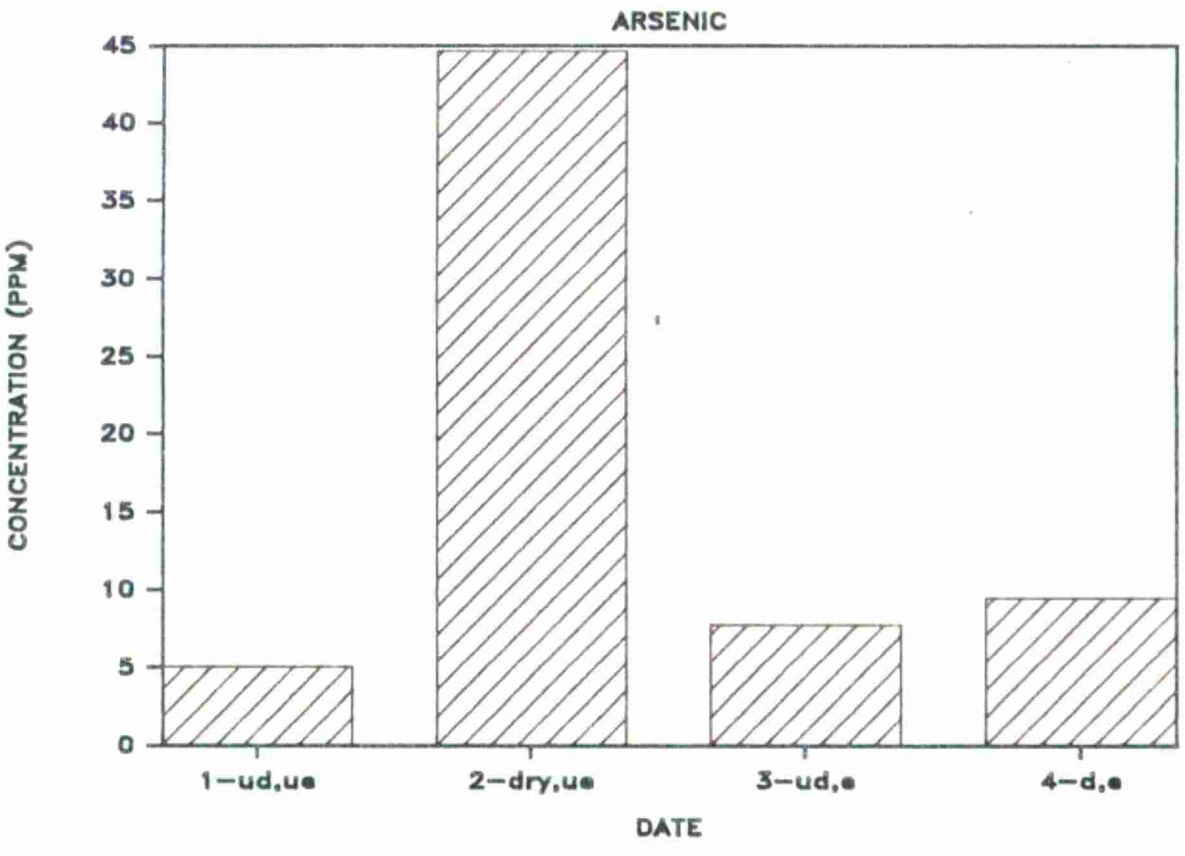
TOTAL METALS COMBINED

SITE 4: DISTURBED, ENRICHED



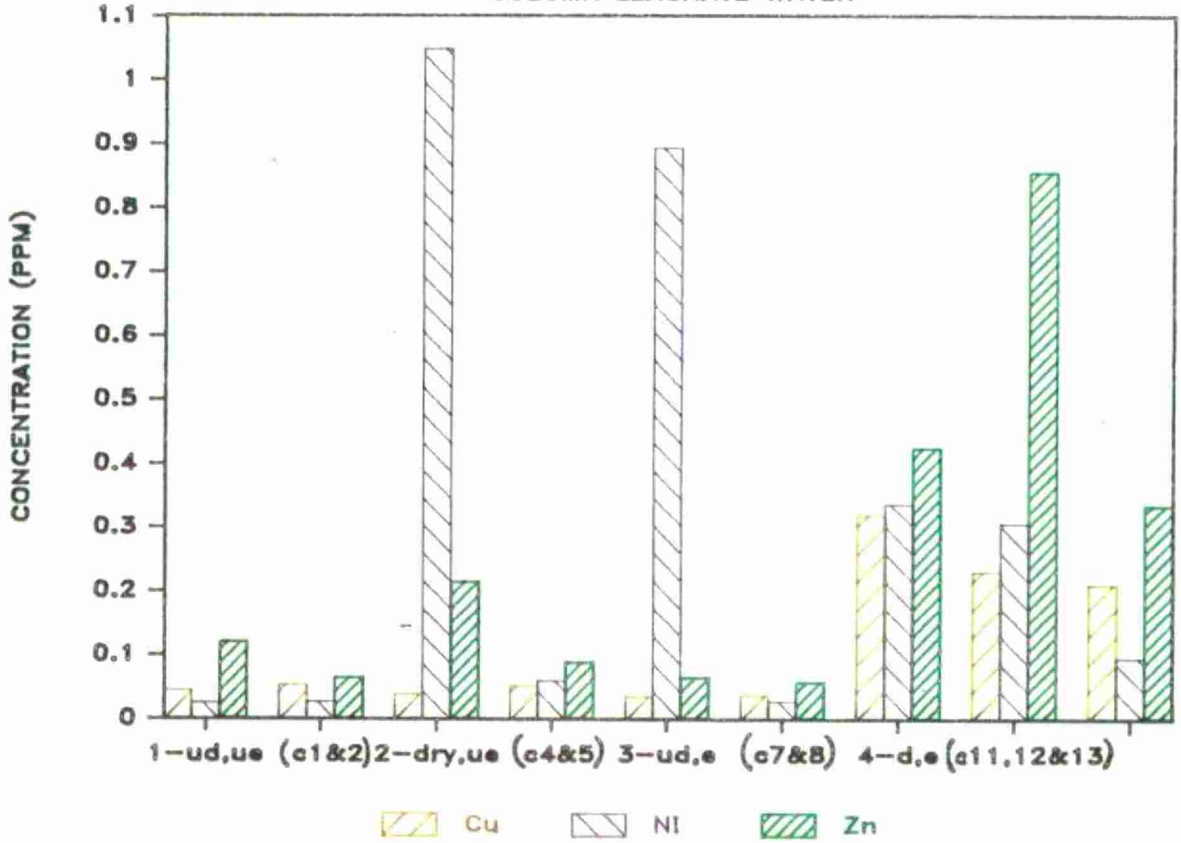
HEAVY METAL CONCENTRATIONS

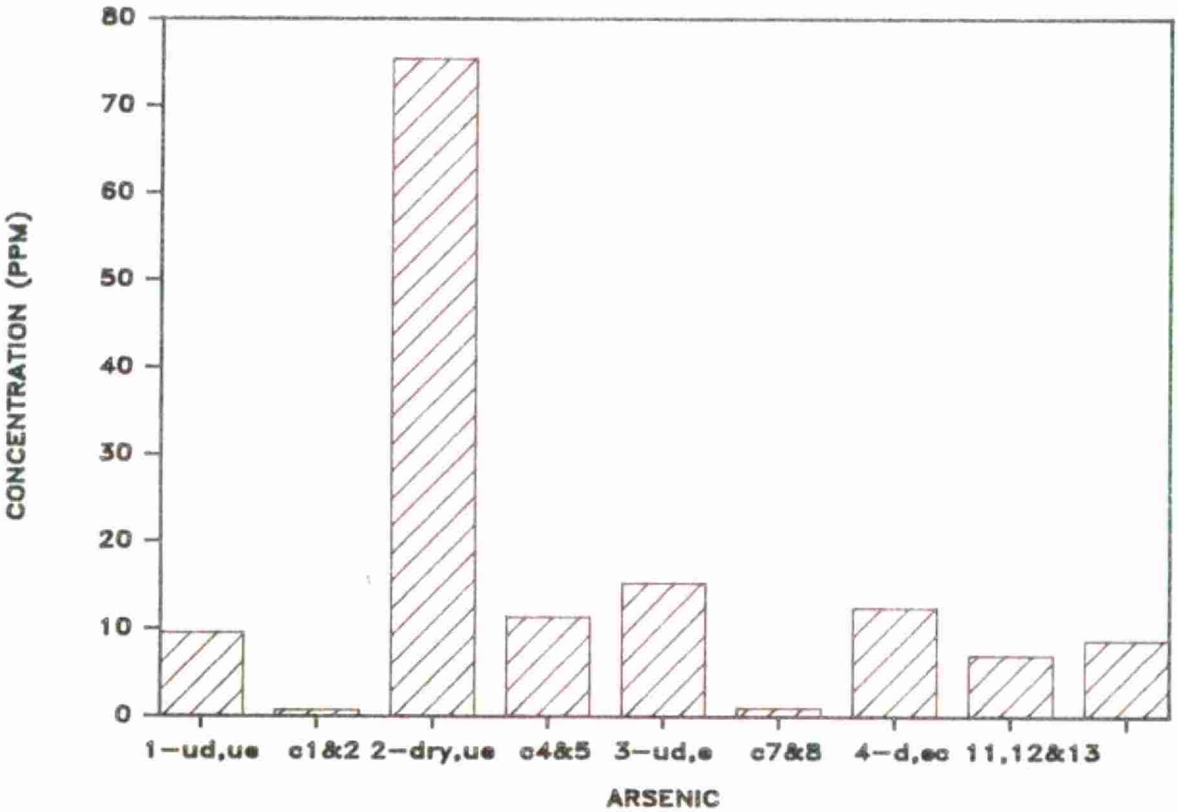




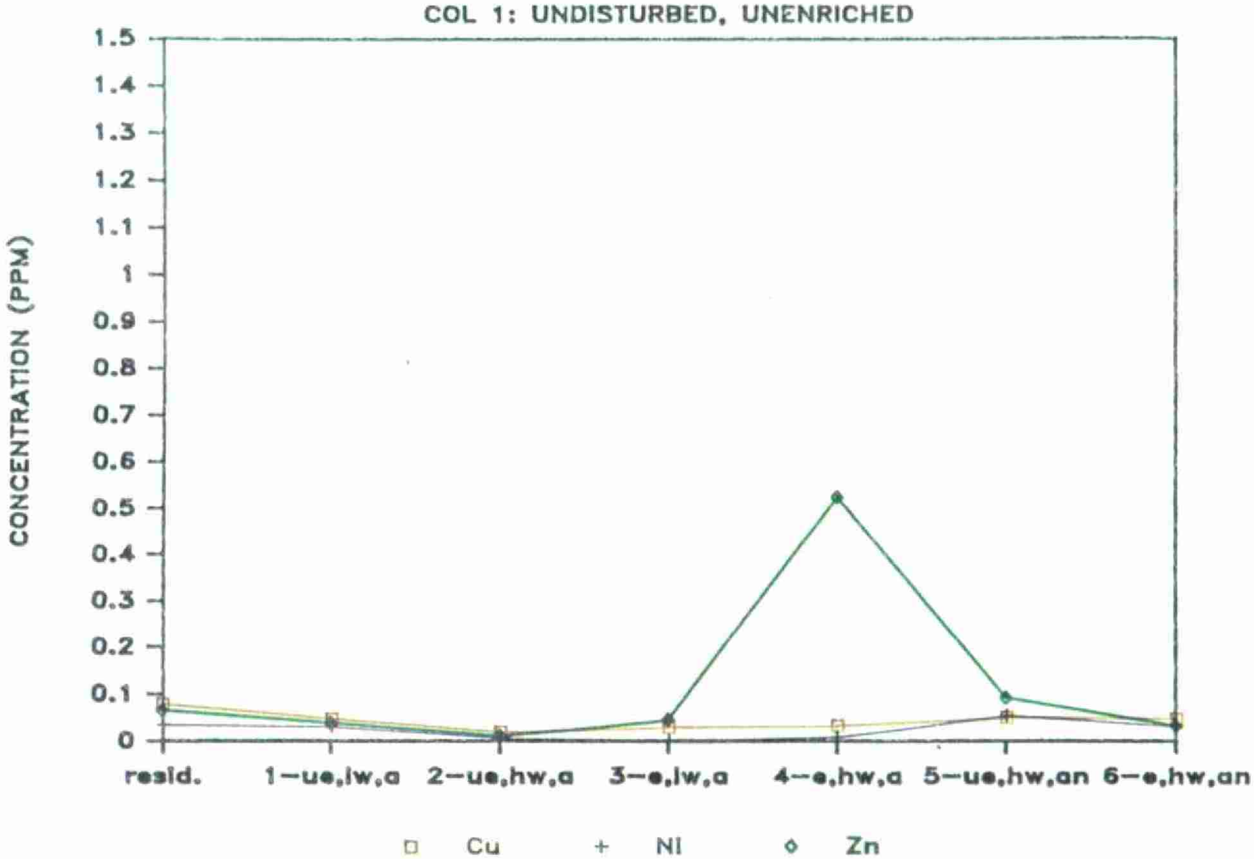
AVERAGE HEAVY METAL CONCENTRATIONS

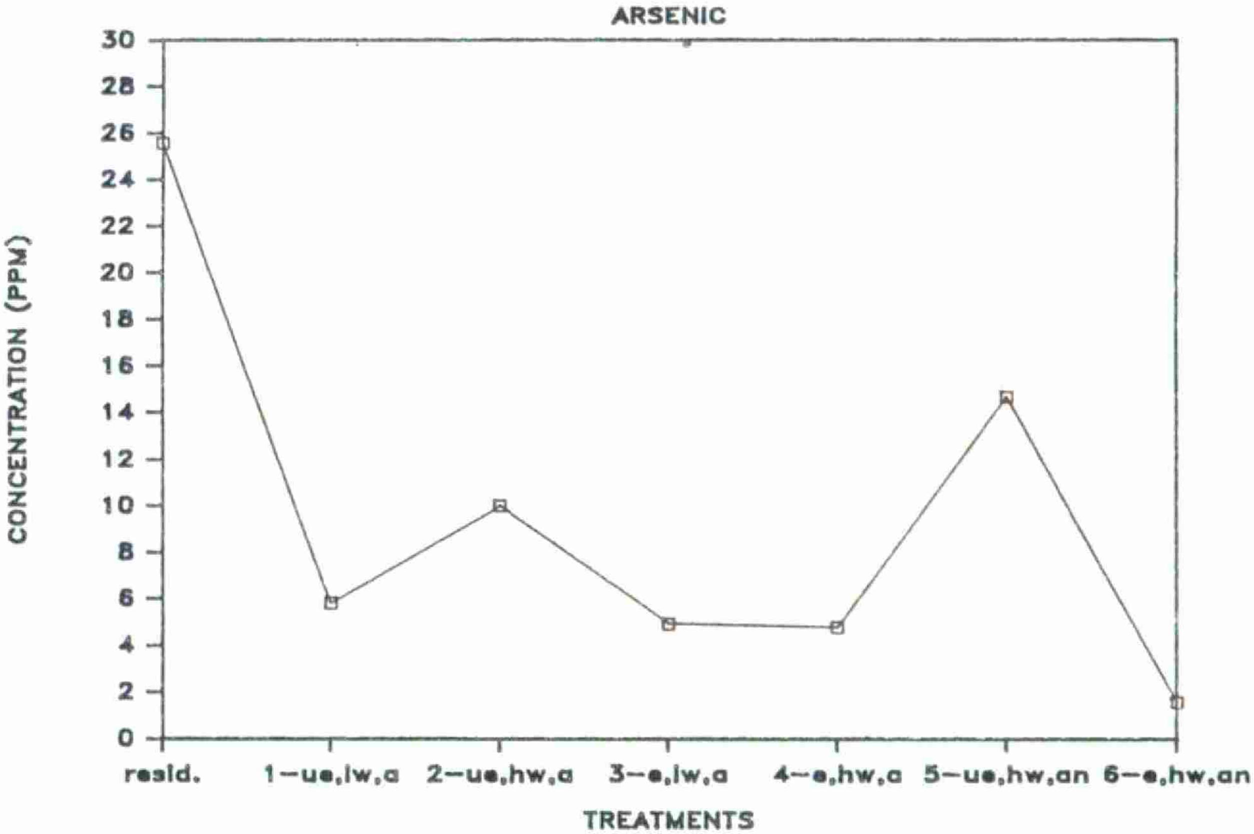
COLUMN LEACHATE WATER



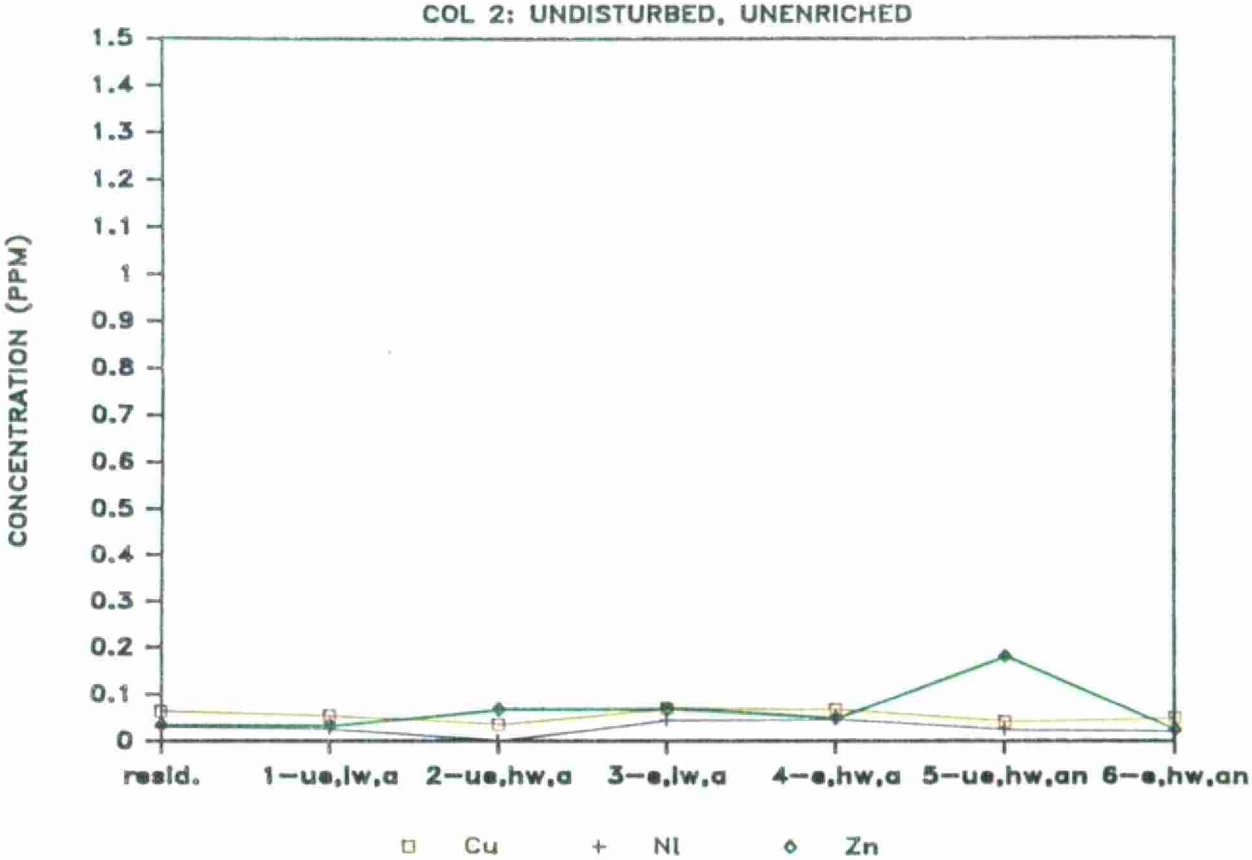


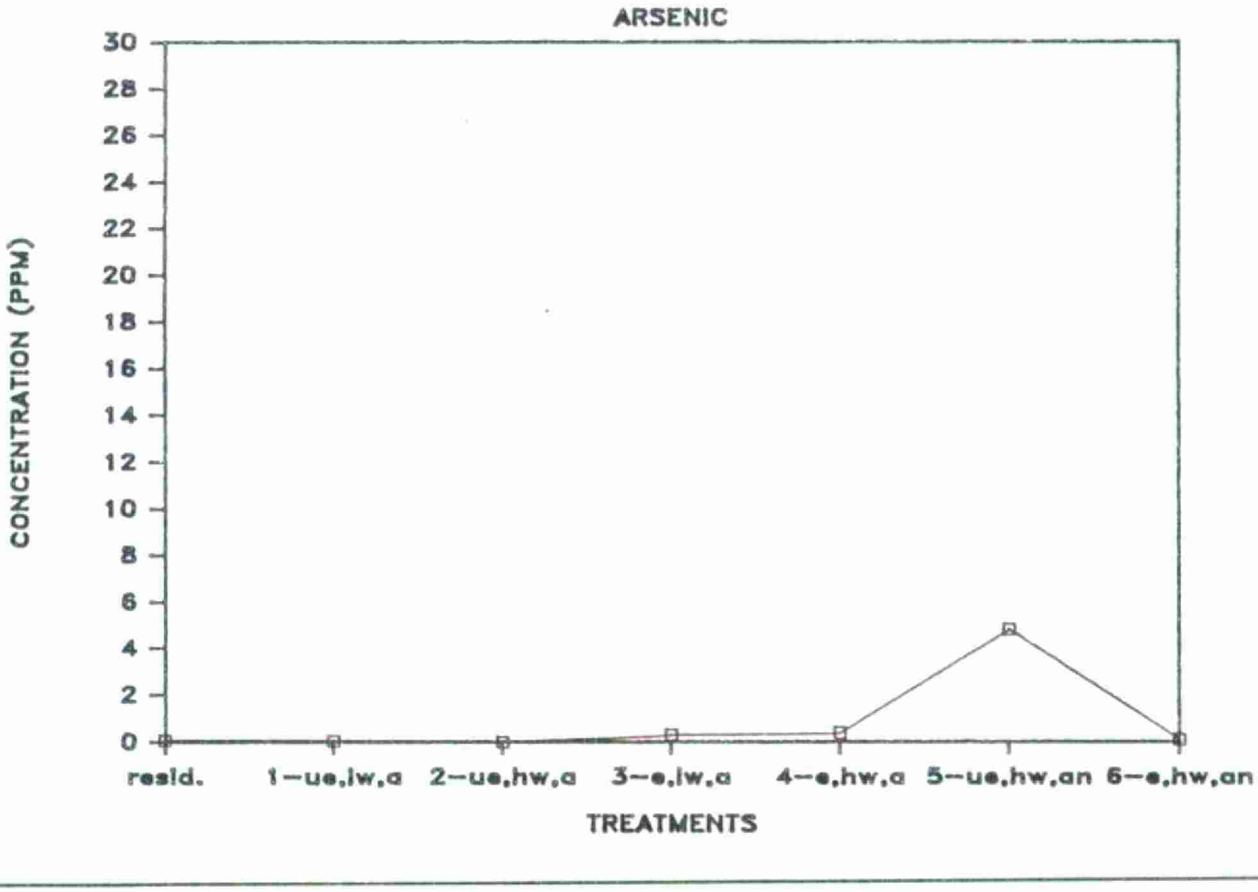
LEACHATE METAL CONCENTRATIONS



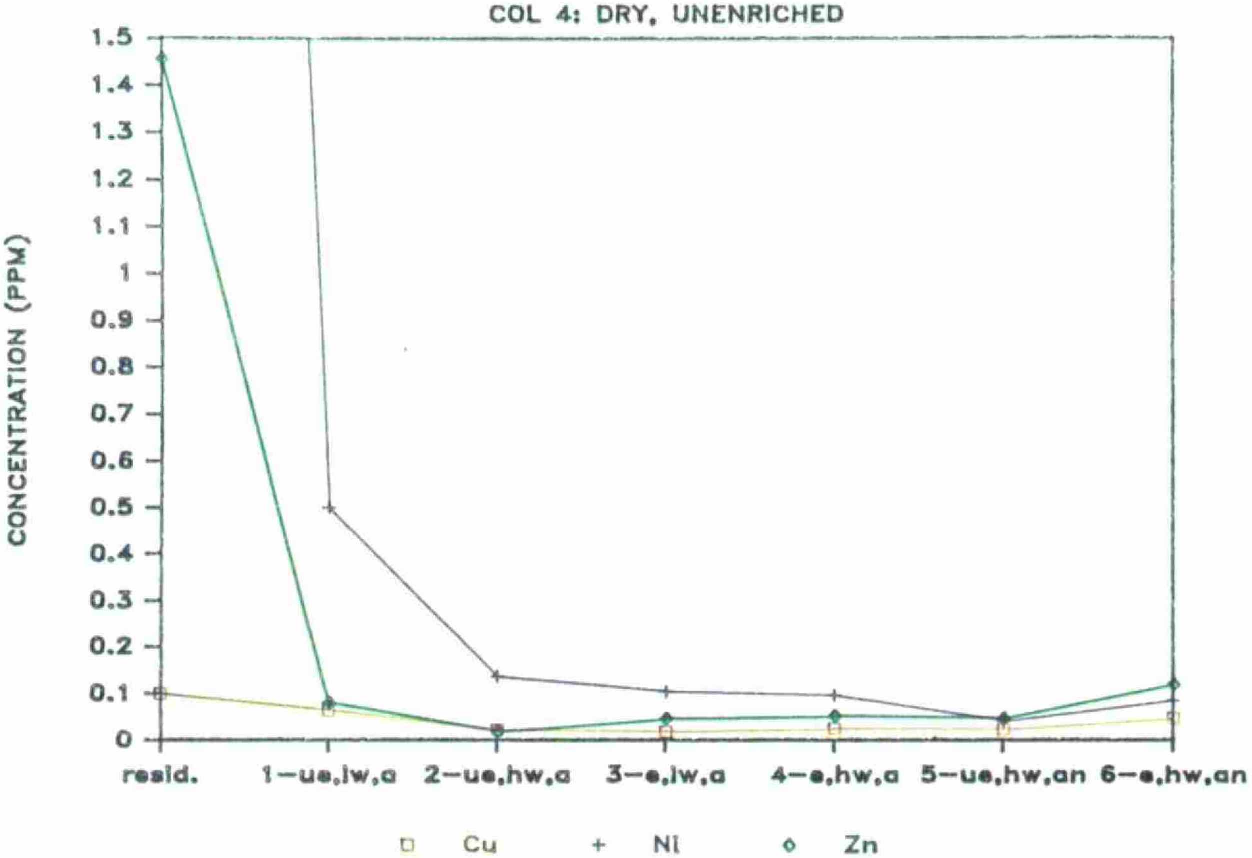


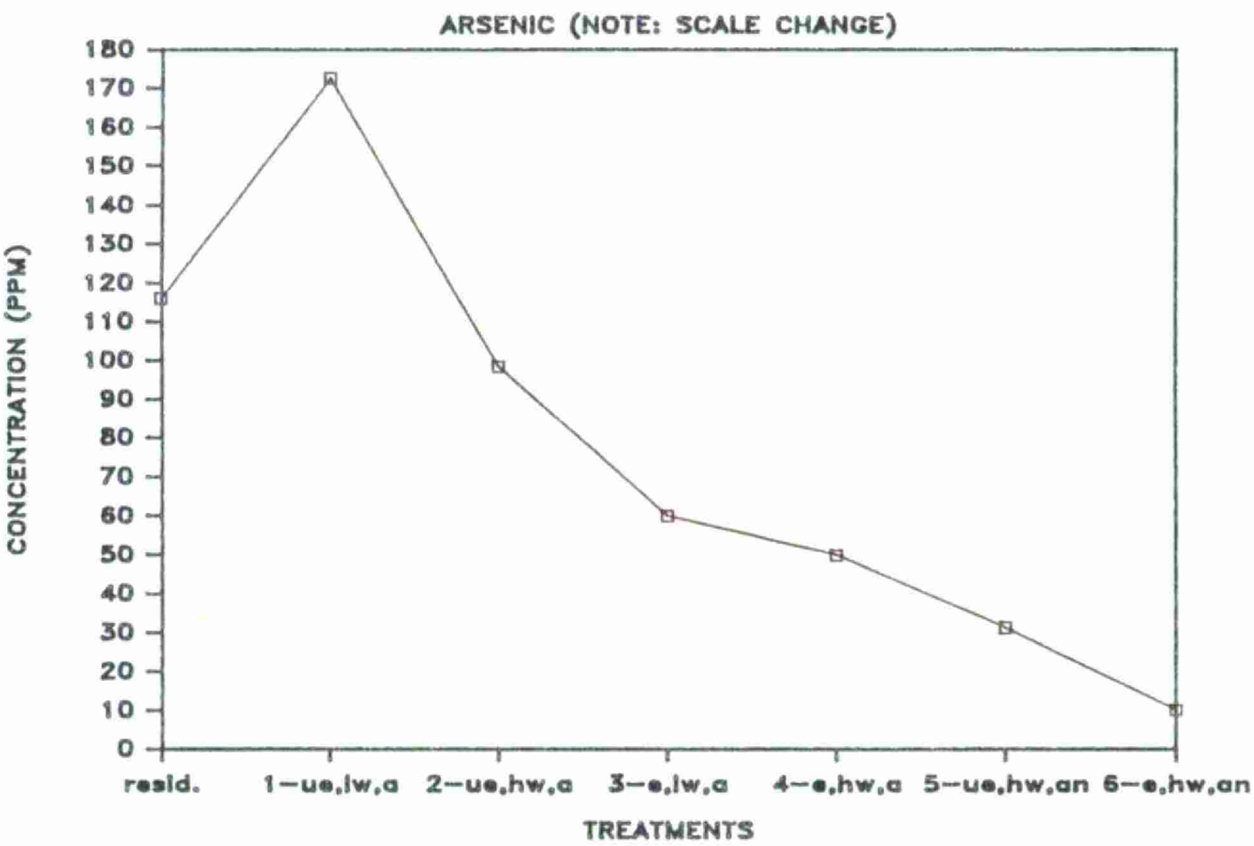
LEACHATE METAL CONCENTRATIONS



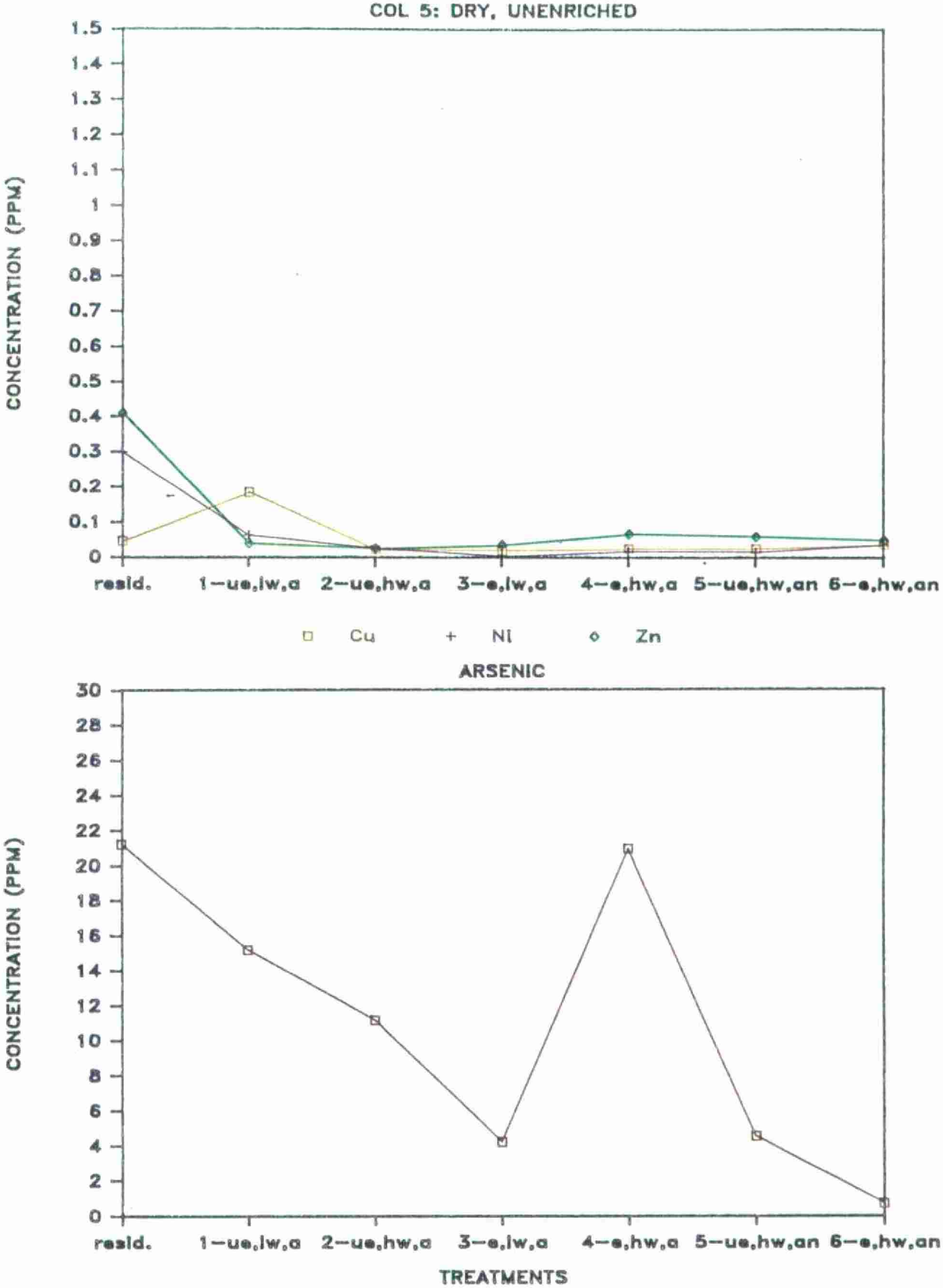


LEACHATE METAL CONCENTRATIONS

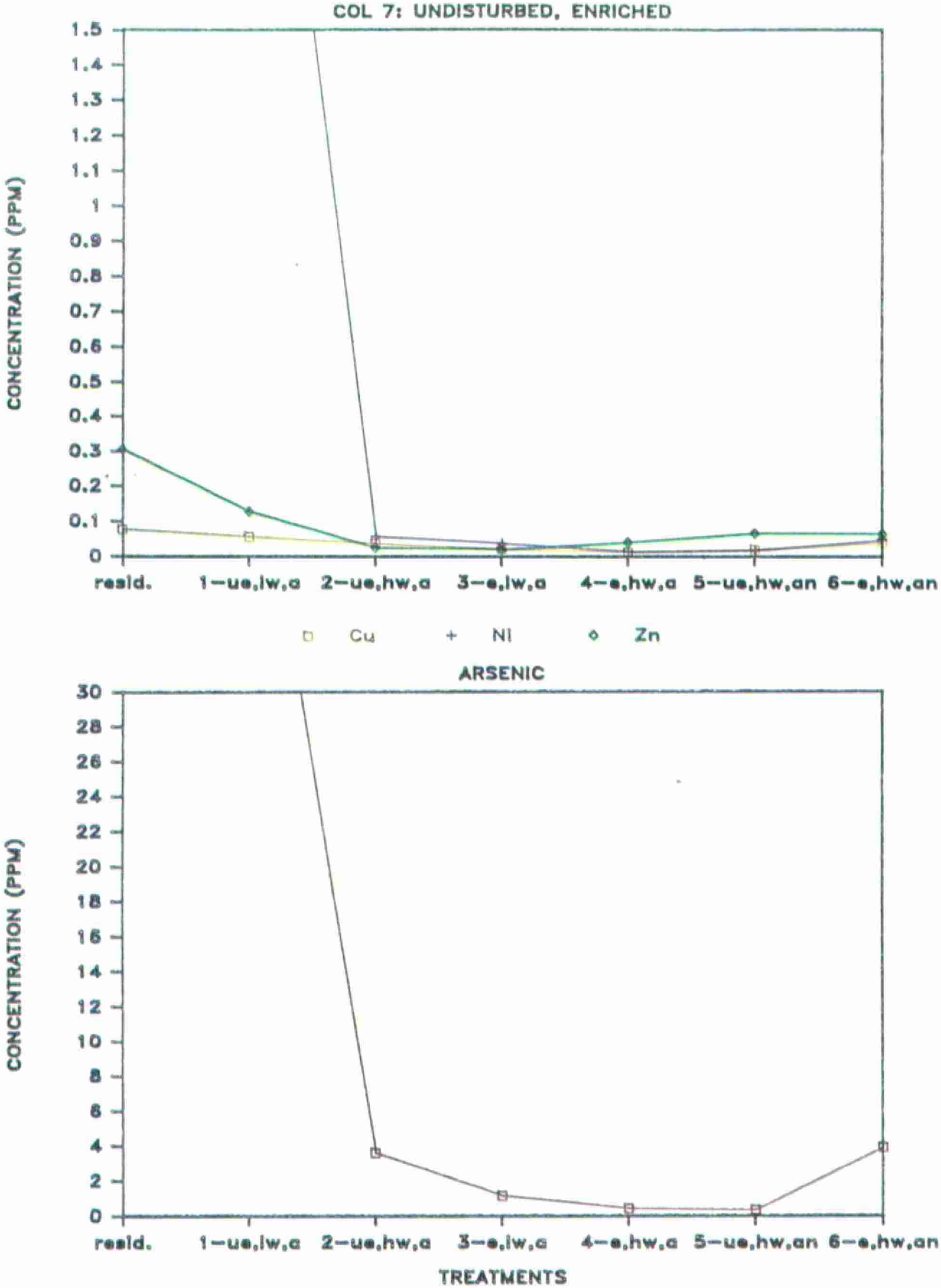




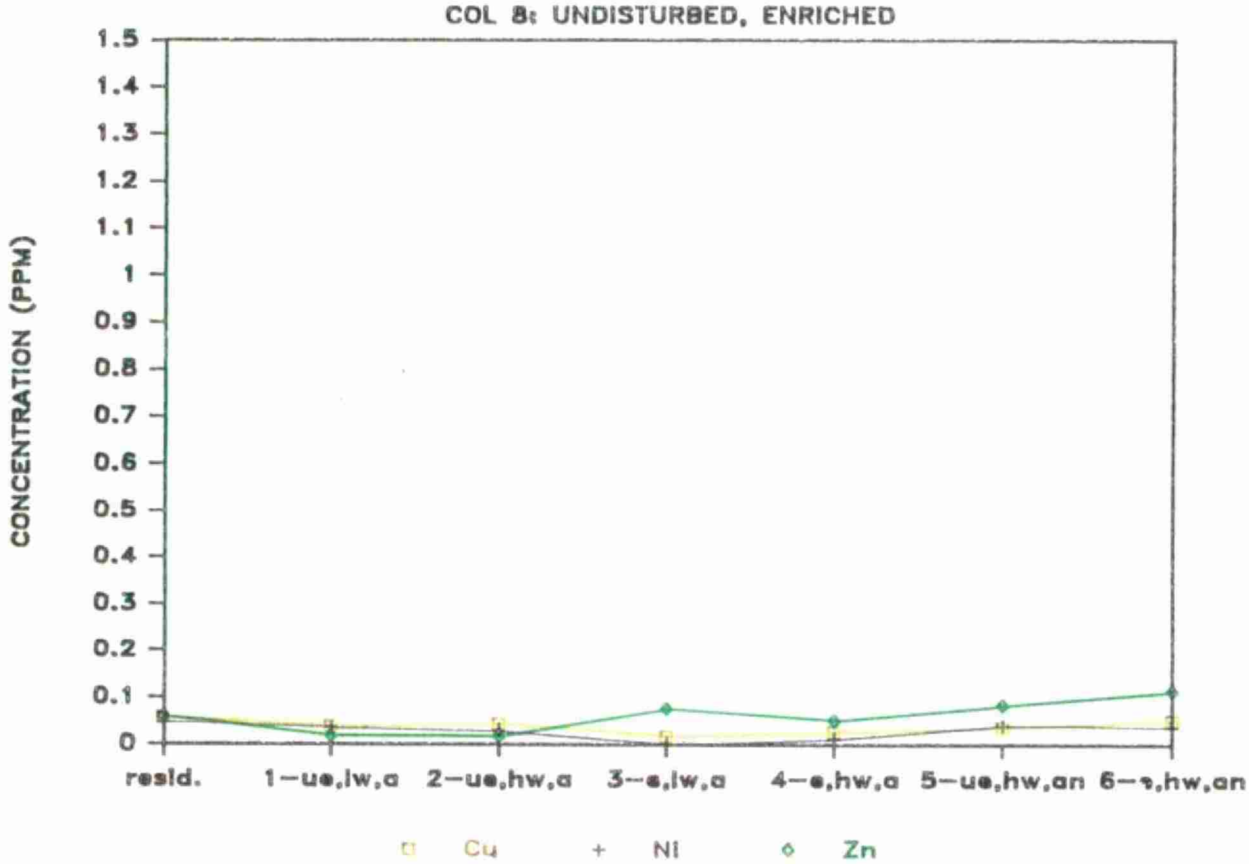
LEACHATE METAL CONCENTRATIONS

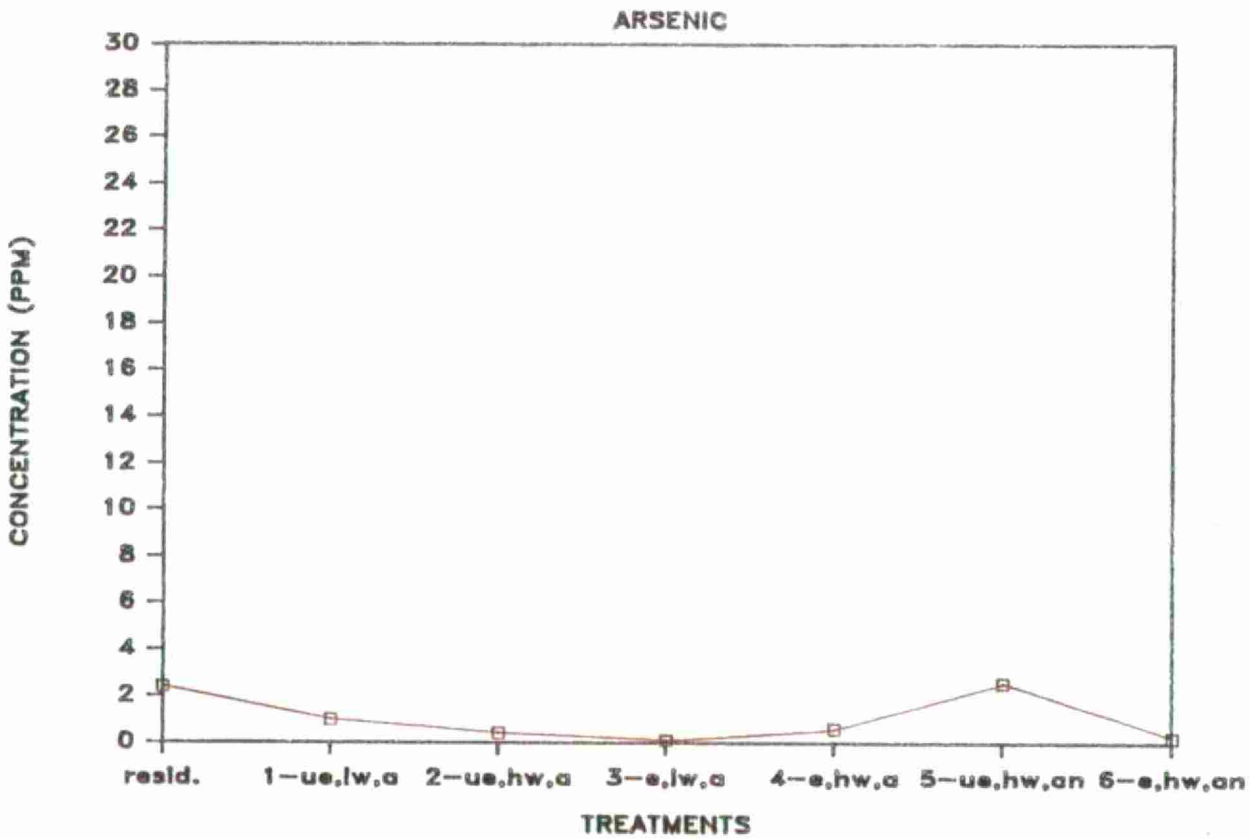


LEACHATE METAL CONCENTRATIONS

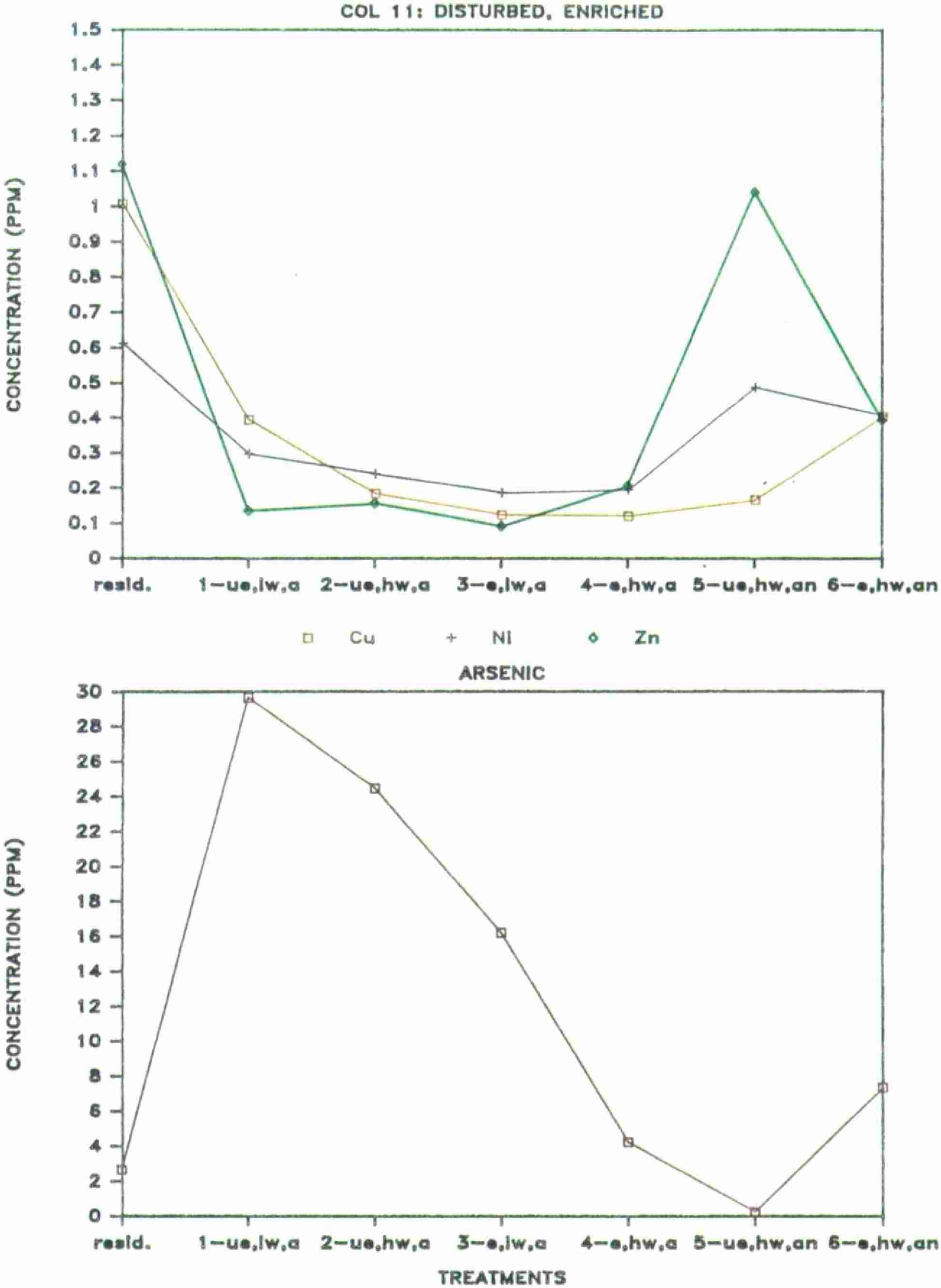


LEACHATE METAL CONCENTRATIONS

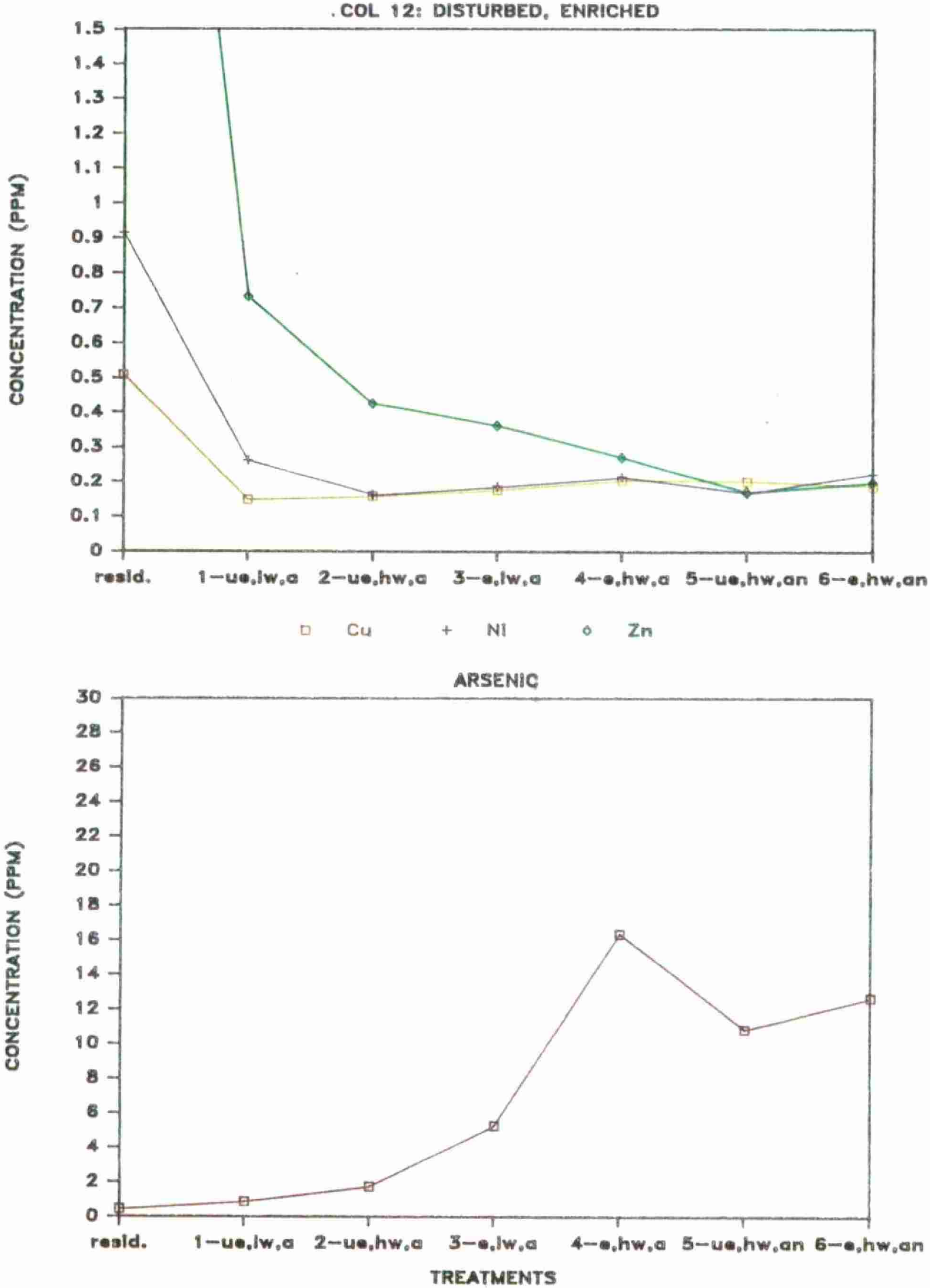




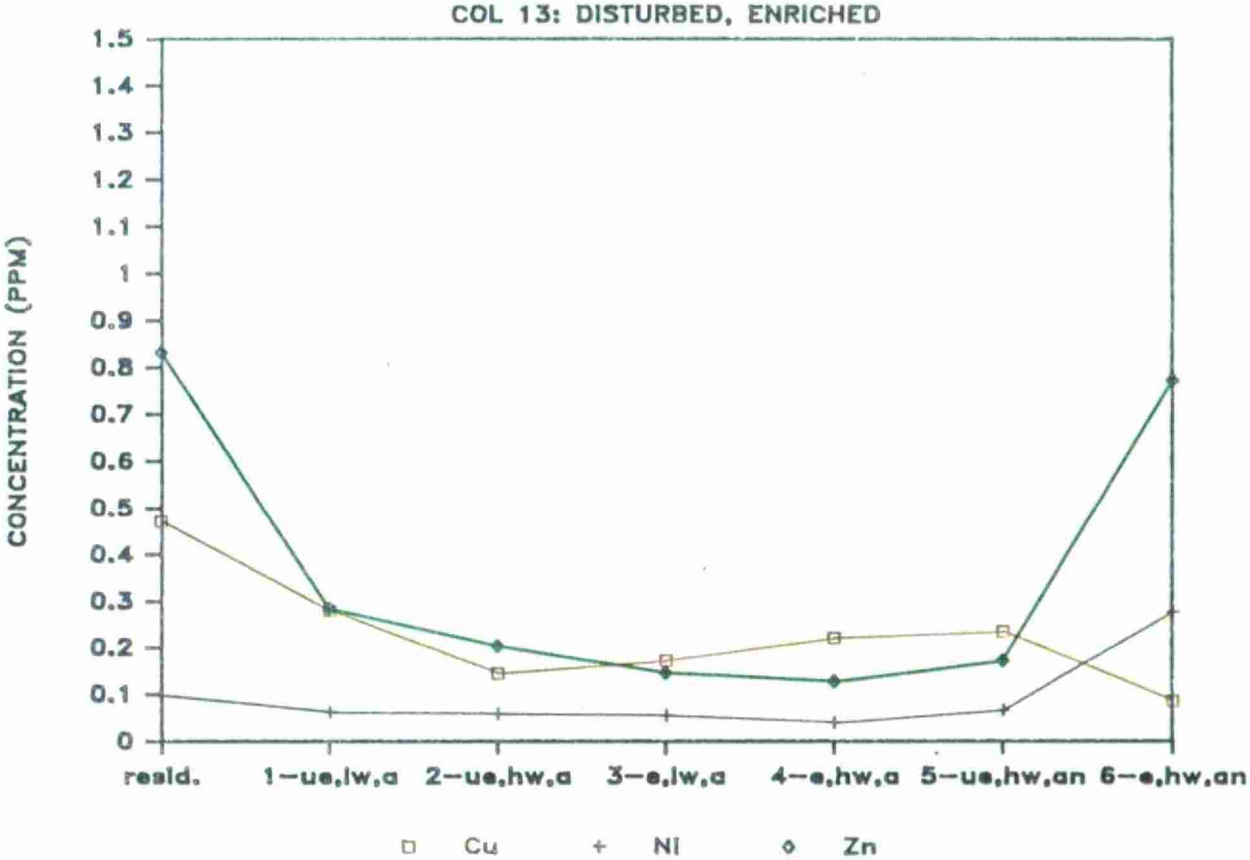
LEACHATE METAL CONCENTRATIONS

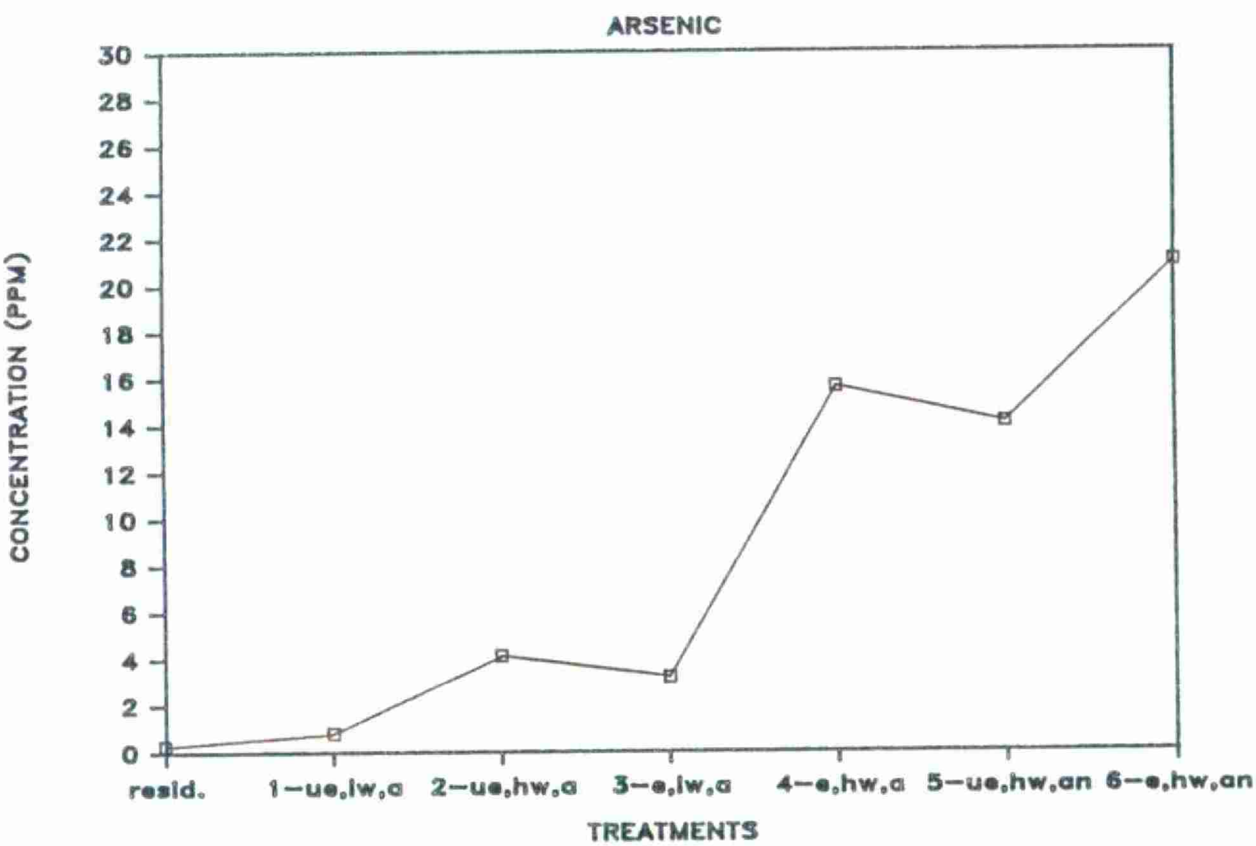


LEACHATE METAL CONCENTRATIONS

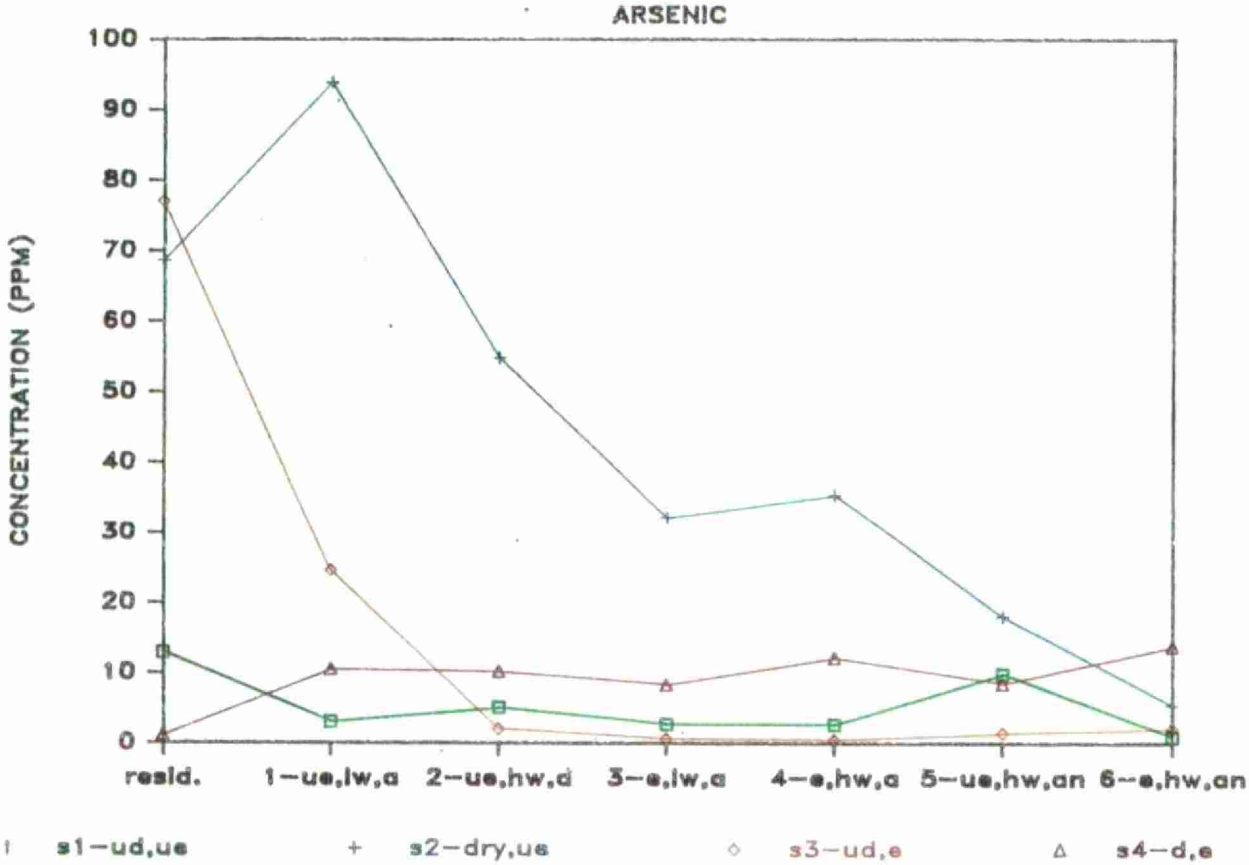


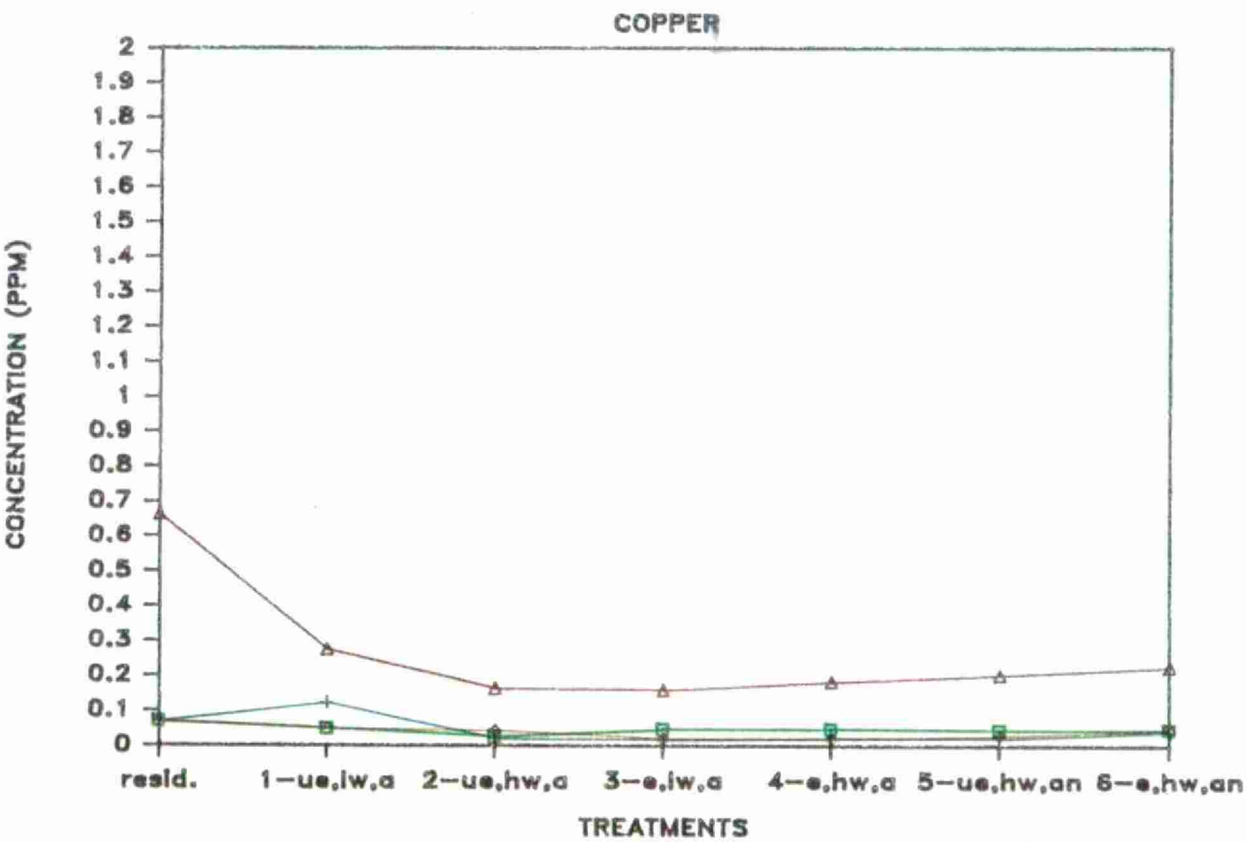
LEACHATE METAL CONCENTRATIONS



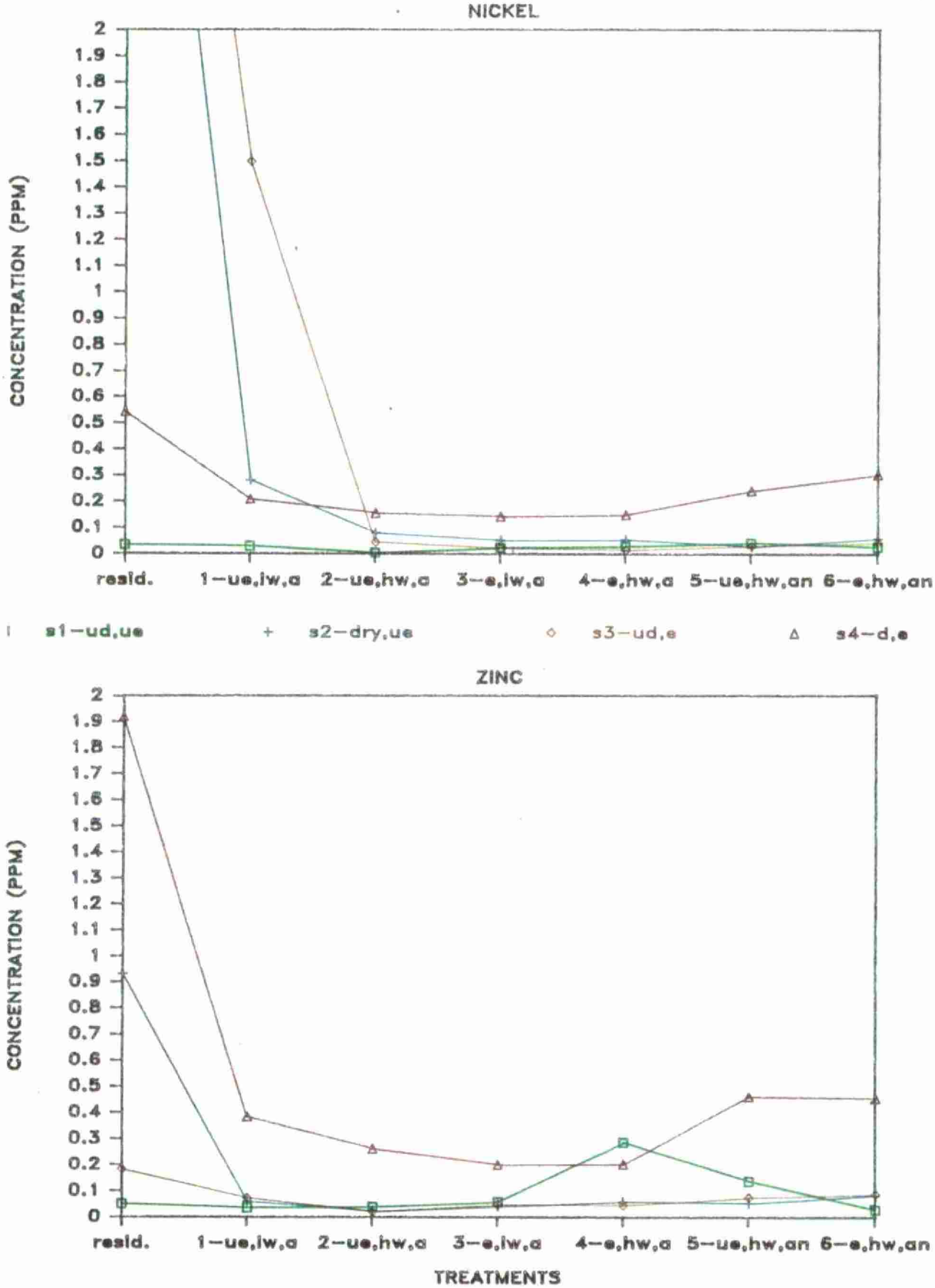


LEACHATE CONCENTRATIONS AMONG SITES

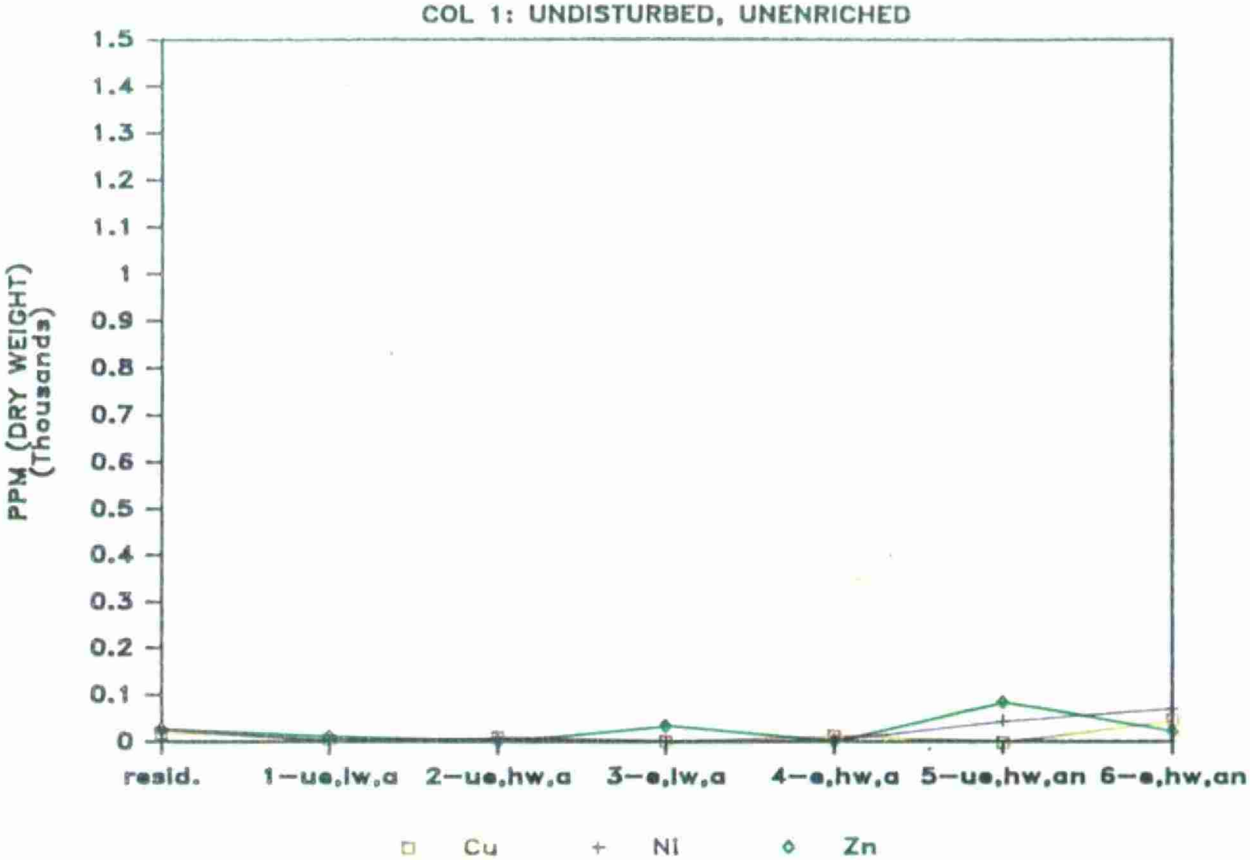


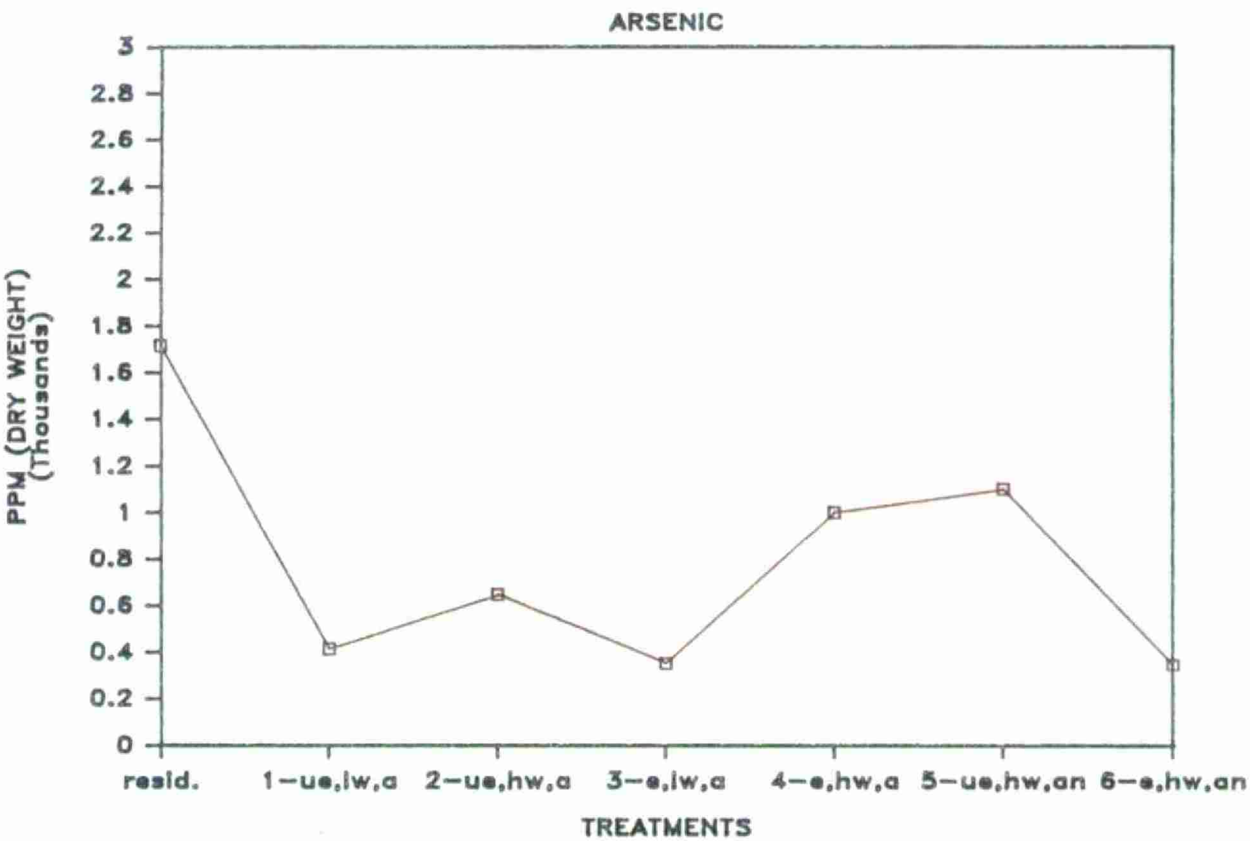


LEACHATE CONCENTRATIONS AMONG SITES

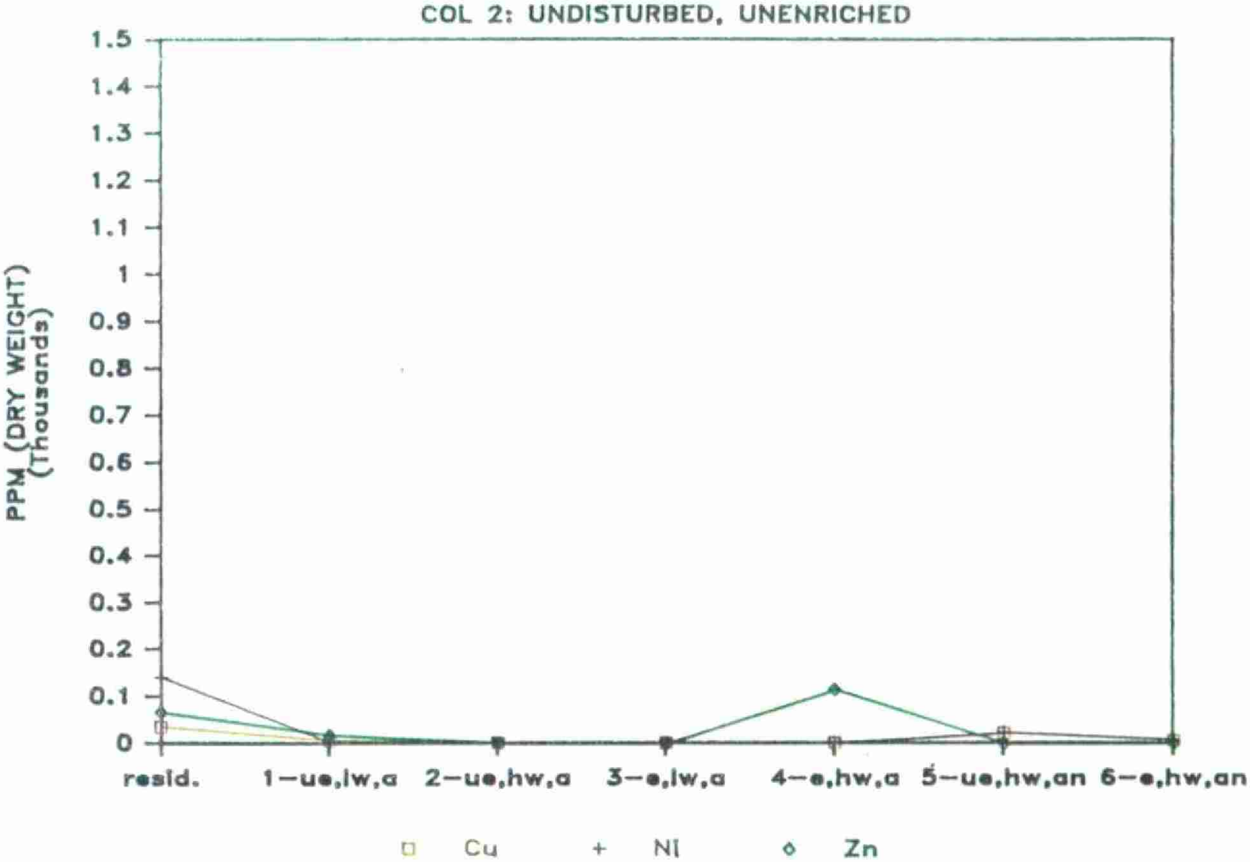


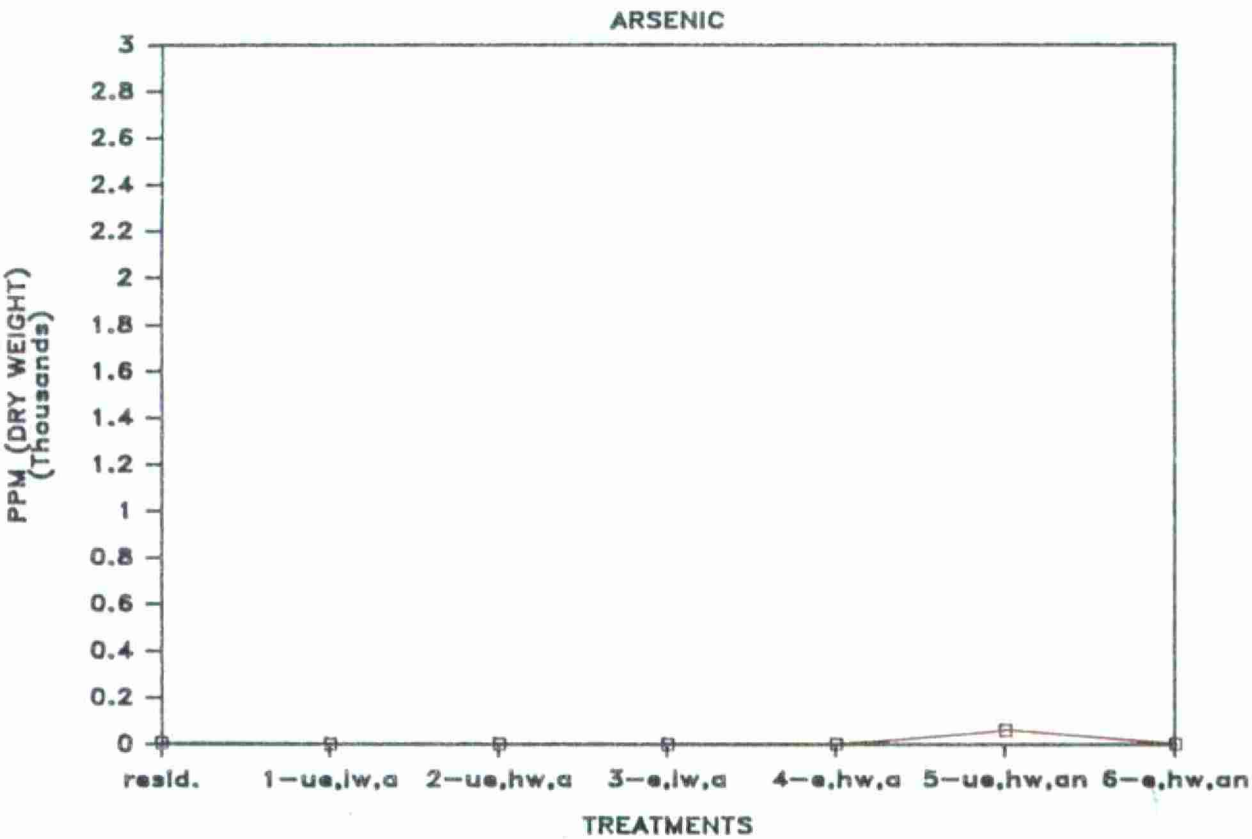
BIOLOGICAL UPTAKE OF HEAVY METALS



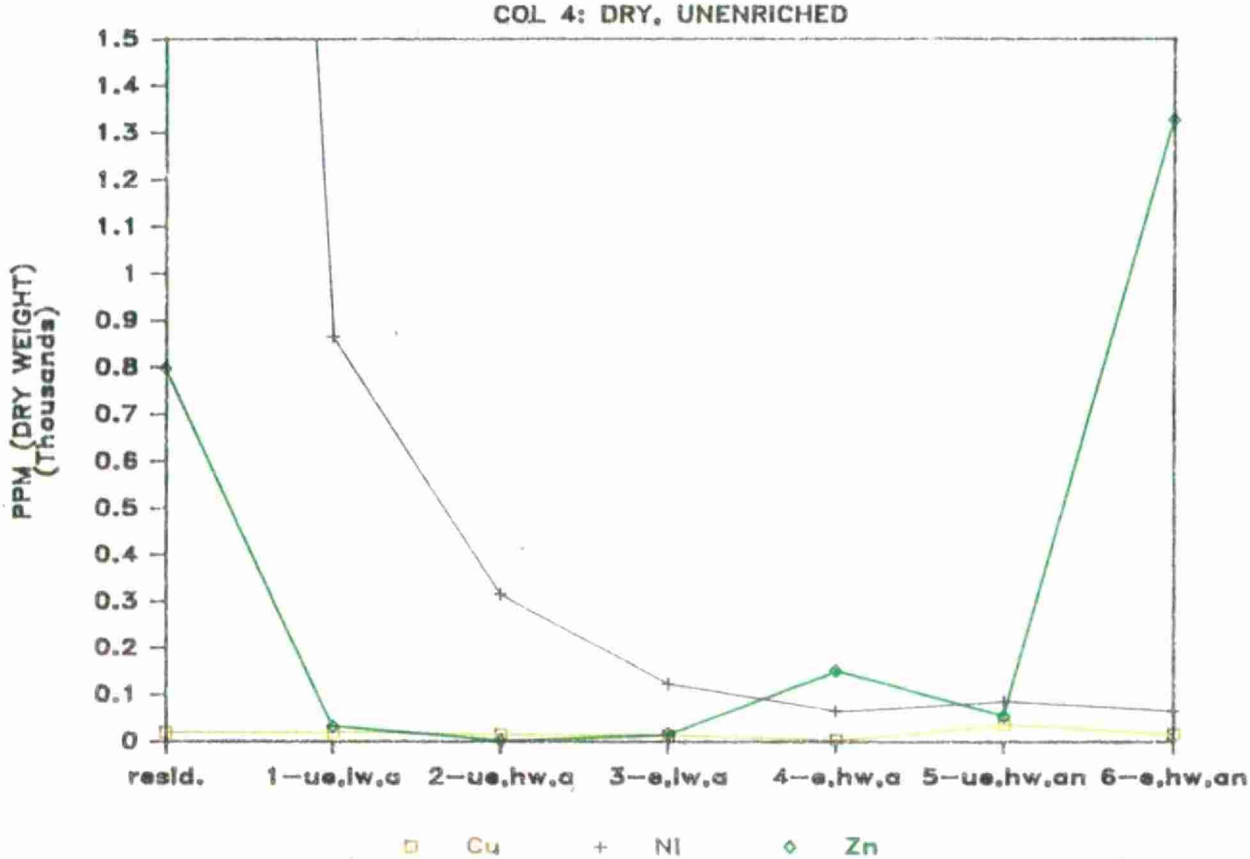


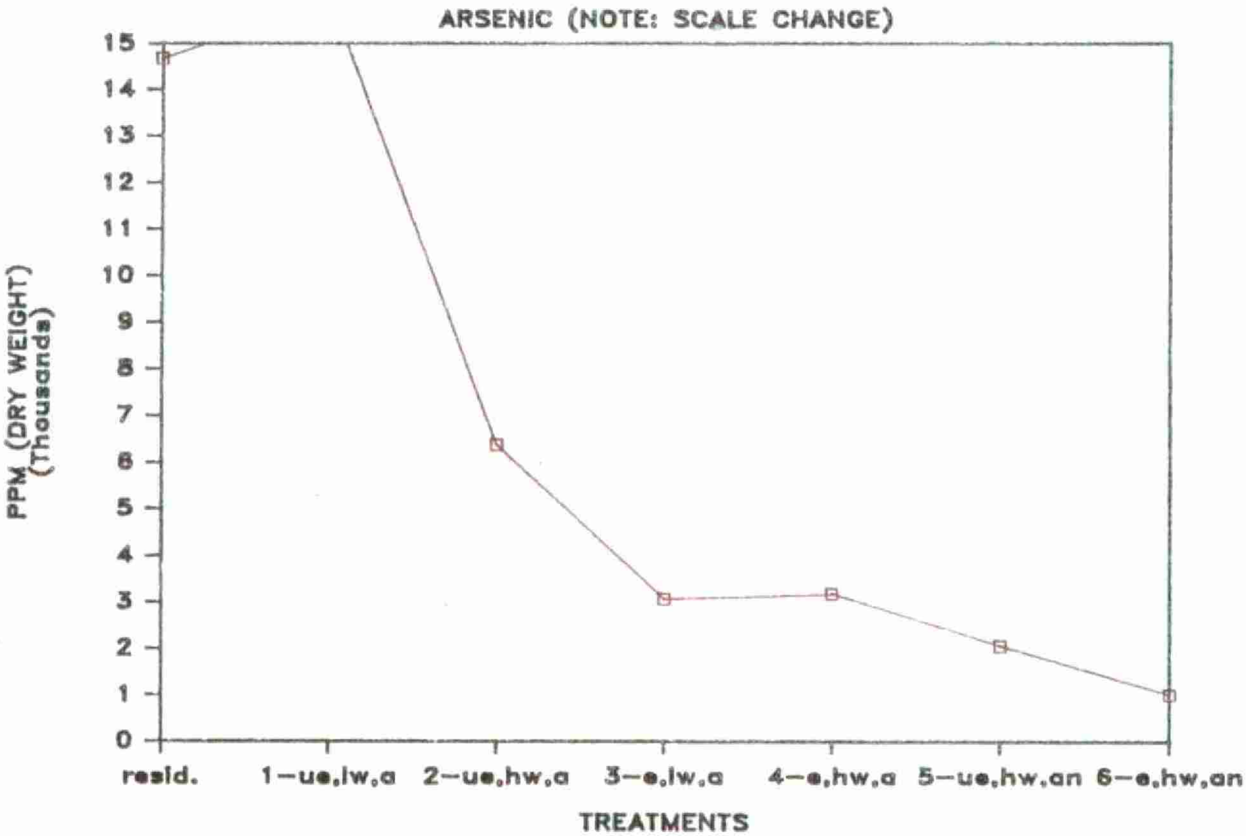
BIOLOGICAL UPTAKE OF HEAVY METALS

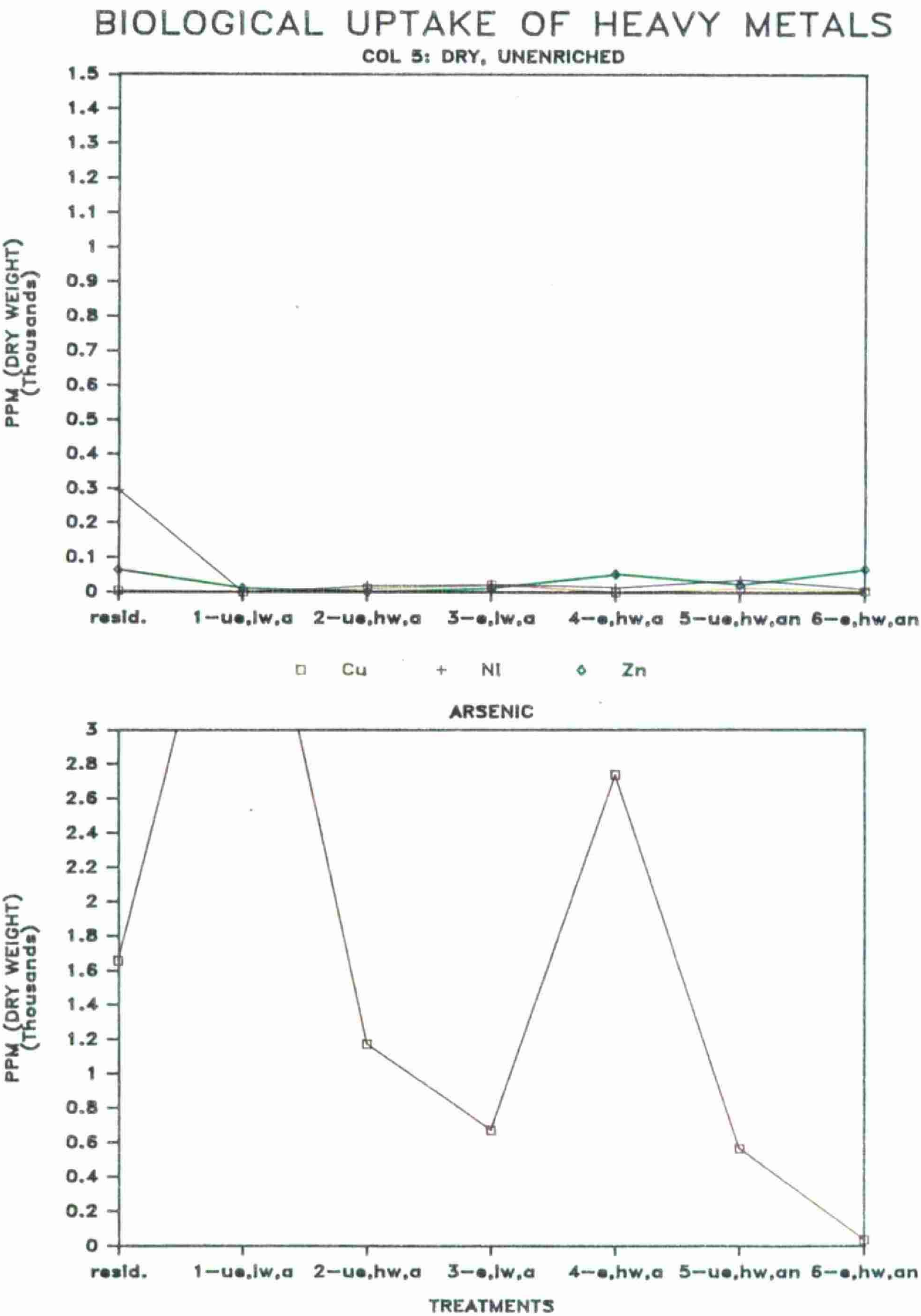




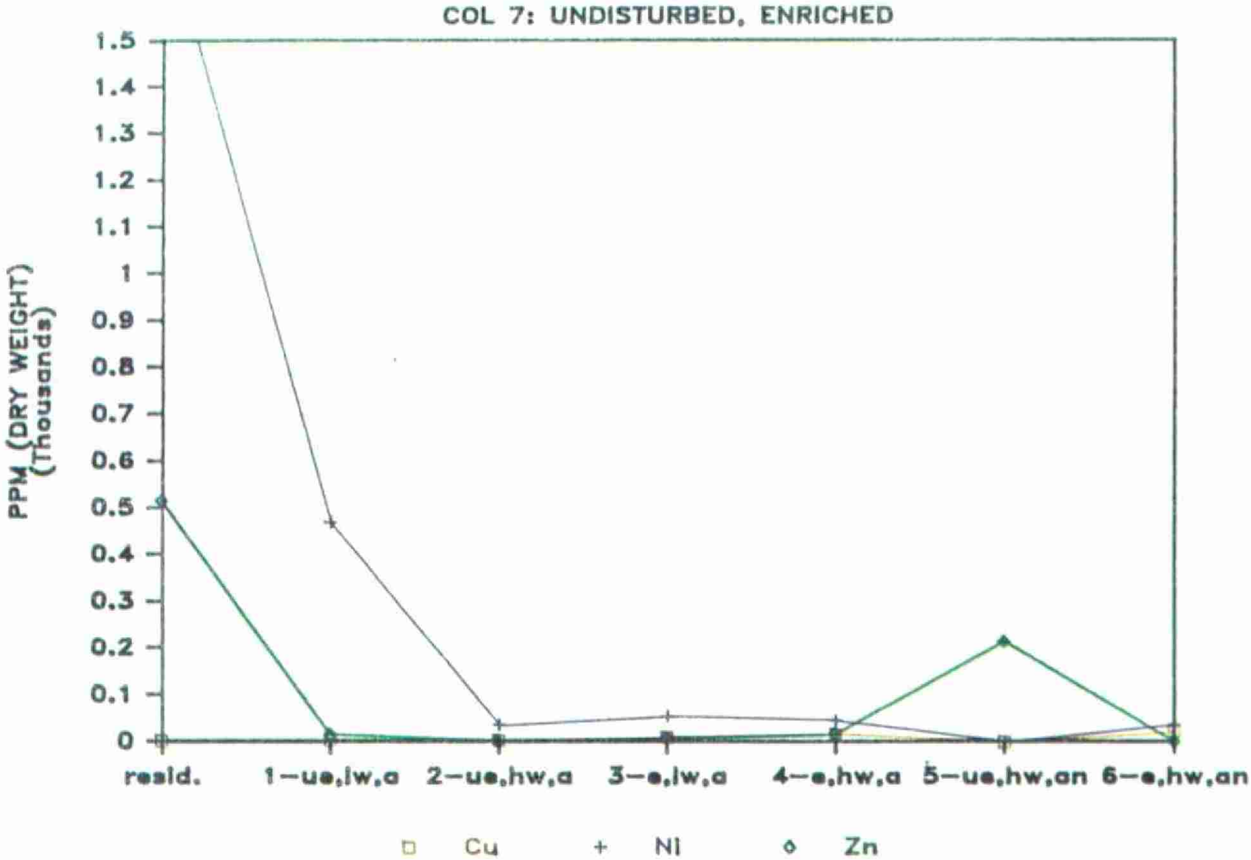
BIOLOGICAL UPTAKE OF HEAVY METALS

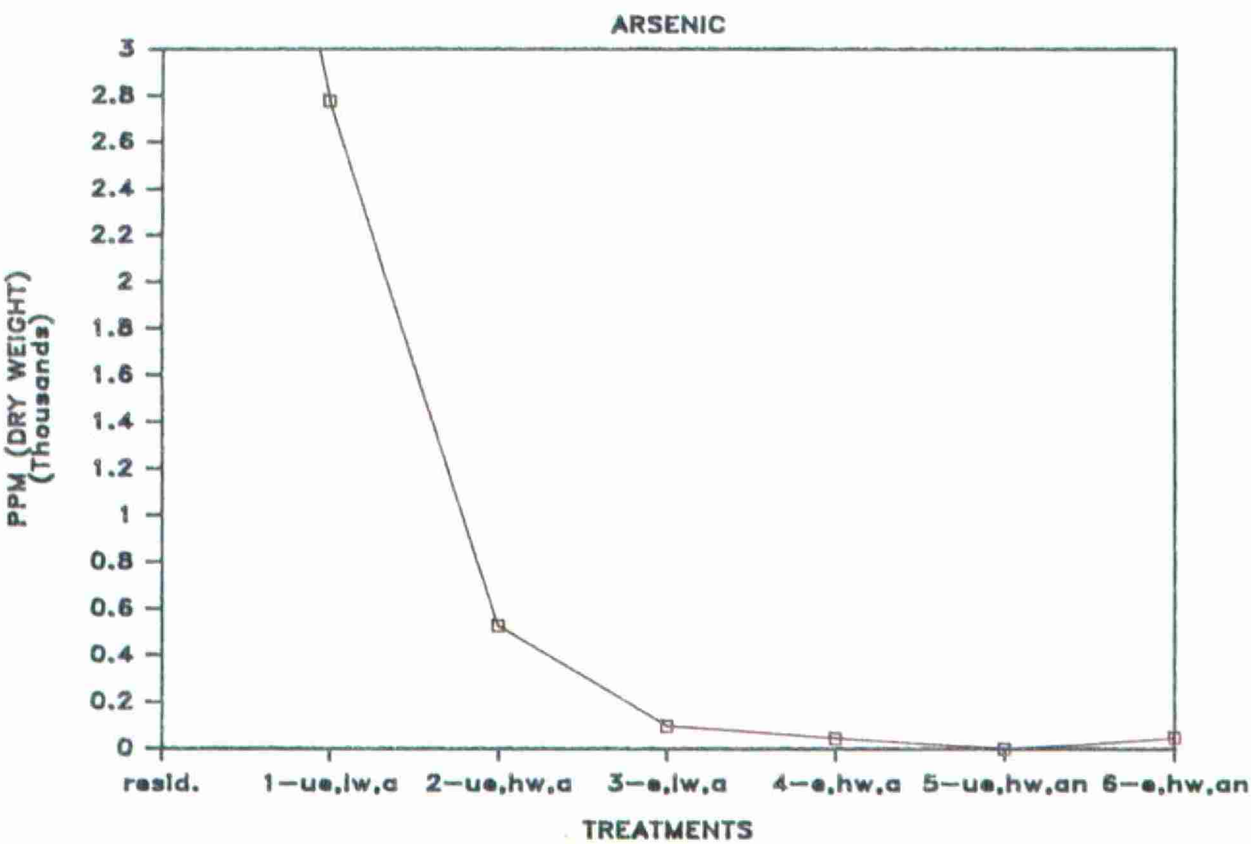




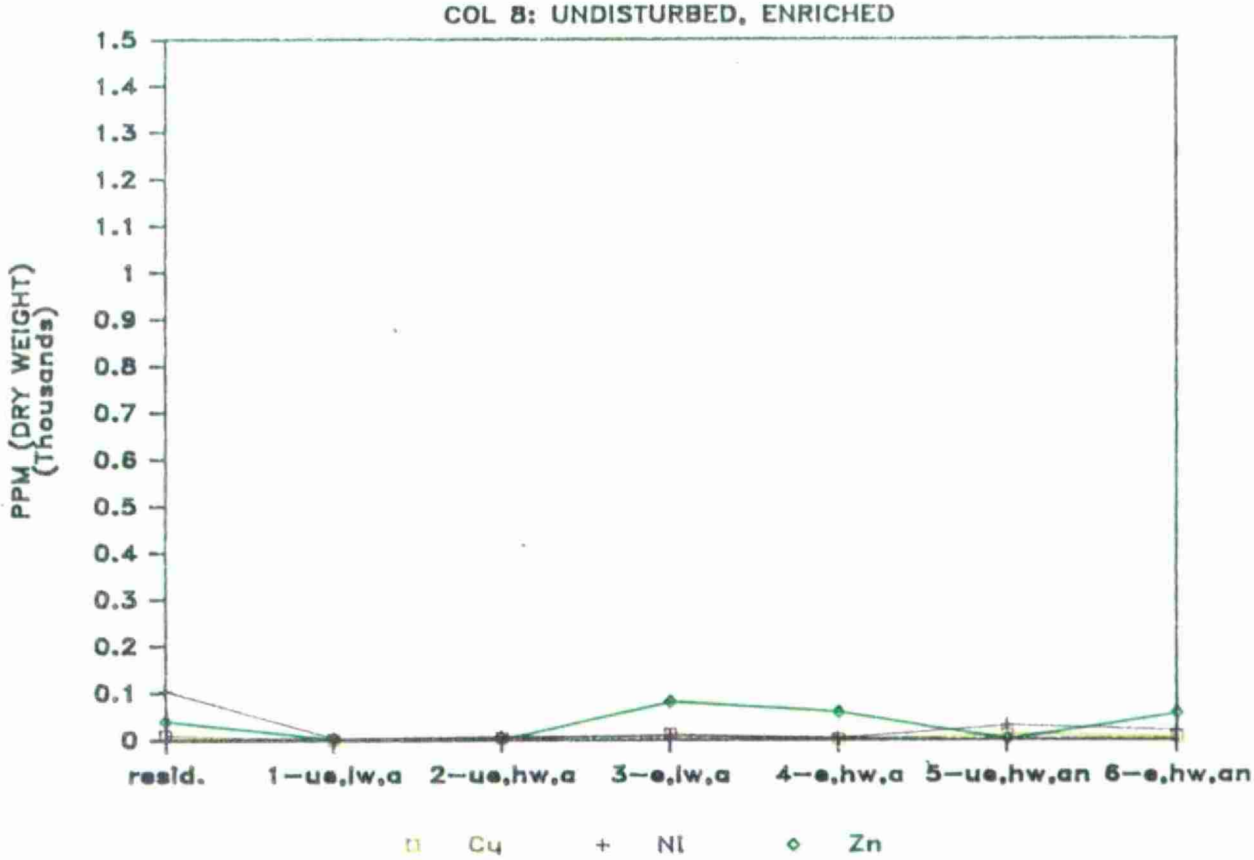

BIOLOGICAL UPTAKE OF HEAVY METALS
COL 5: DRY, UNENRICHED
PPM (DRY WEIGHT) (Thousands)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
resid.
1-ue,lw,a
2-ue,hw,a
3-e,lw,a
4-e,hw,a
5-ue,hw,an
6-e,hw,an
Cu
Ni
Zn
ARSENIC
PPM (DRY WEIGHT) (Thousands)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
resid.
1-ue,lw,a
2-ue,hw,a
3-e,lw,a
4-e,hw,a
5-ue,hw,an
6-e,hw,an
TREATMENTS

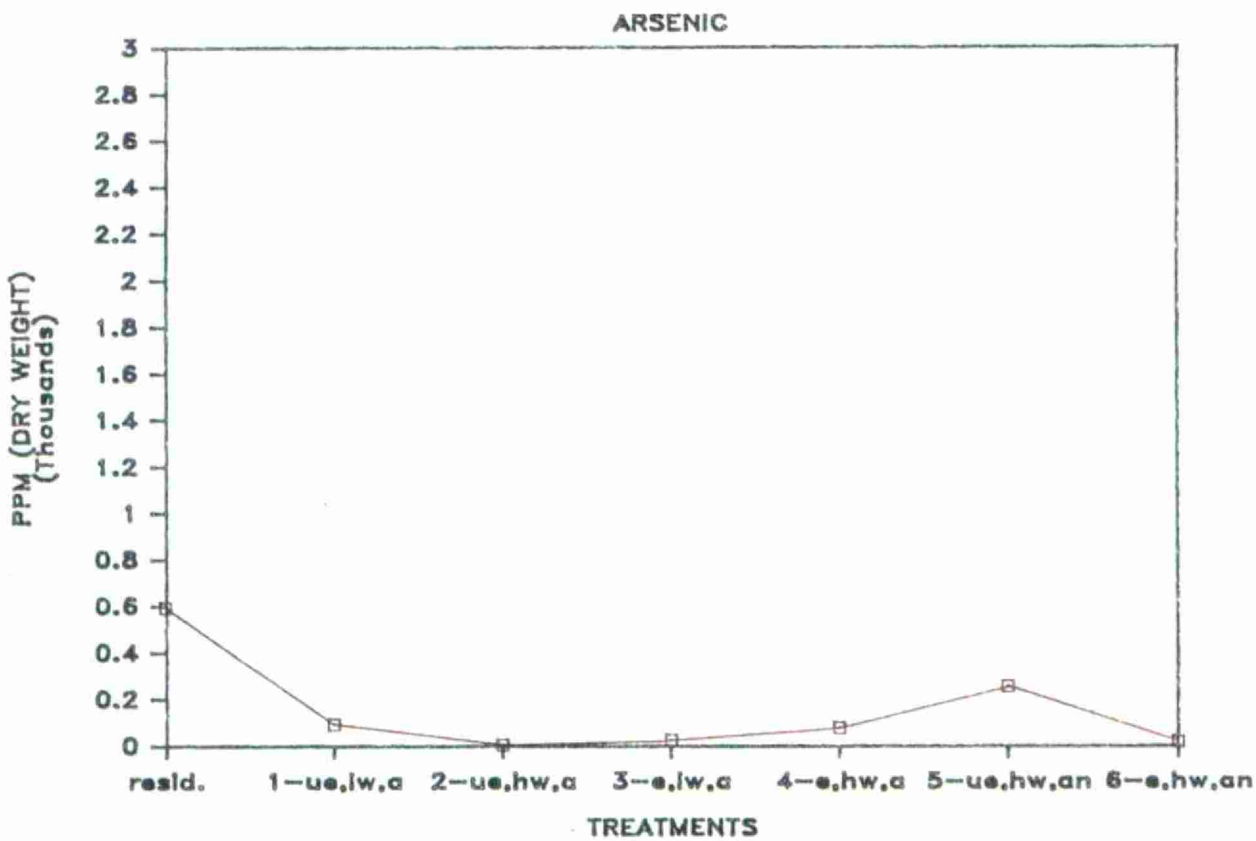
BIOLOGICAL UPTAKE OF HEAVY METALS



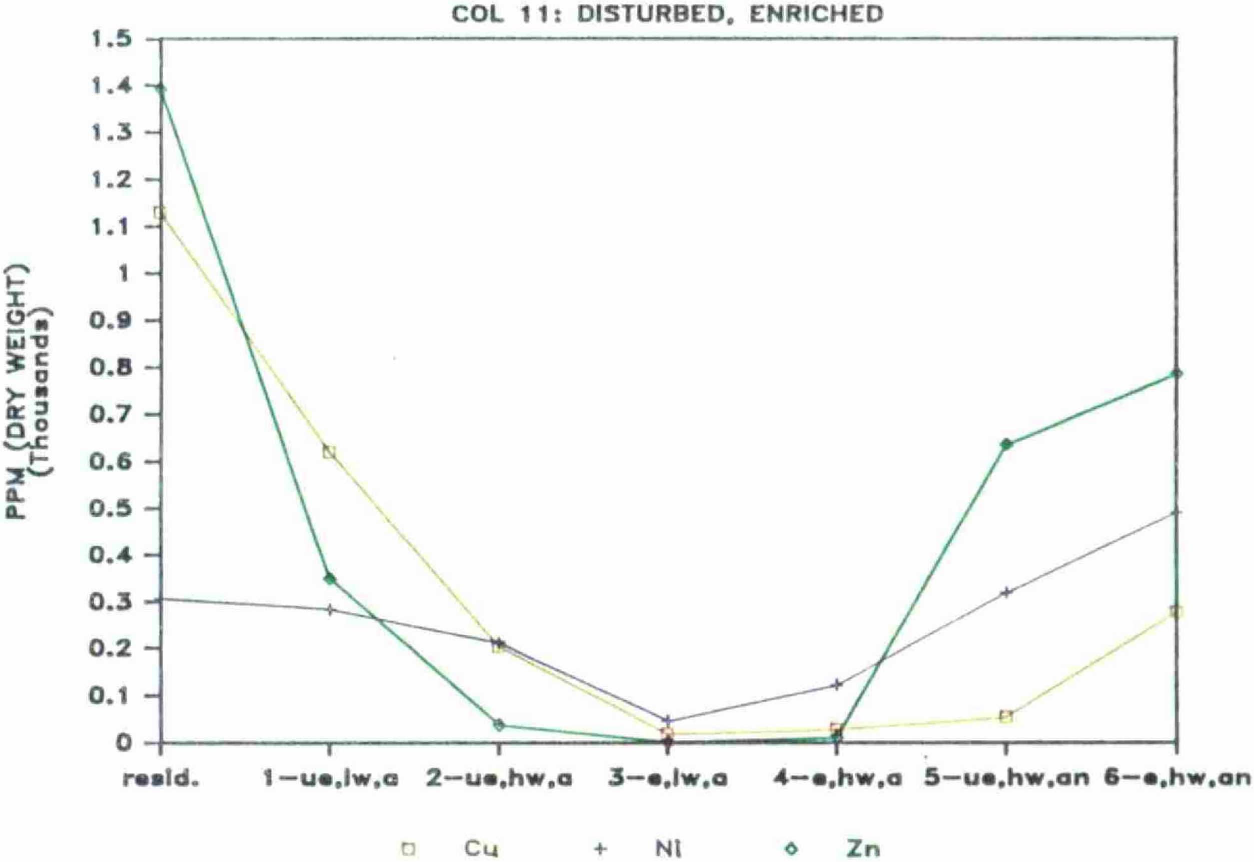


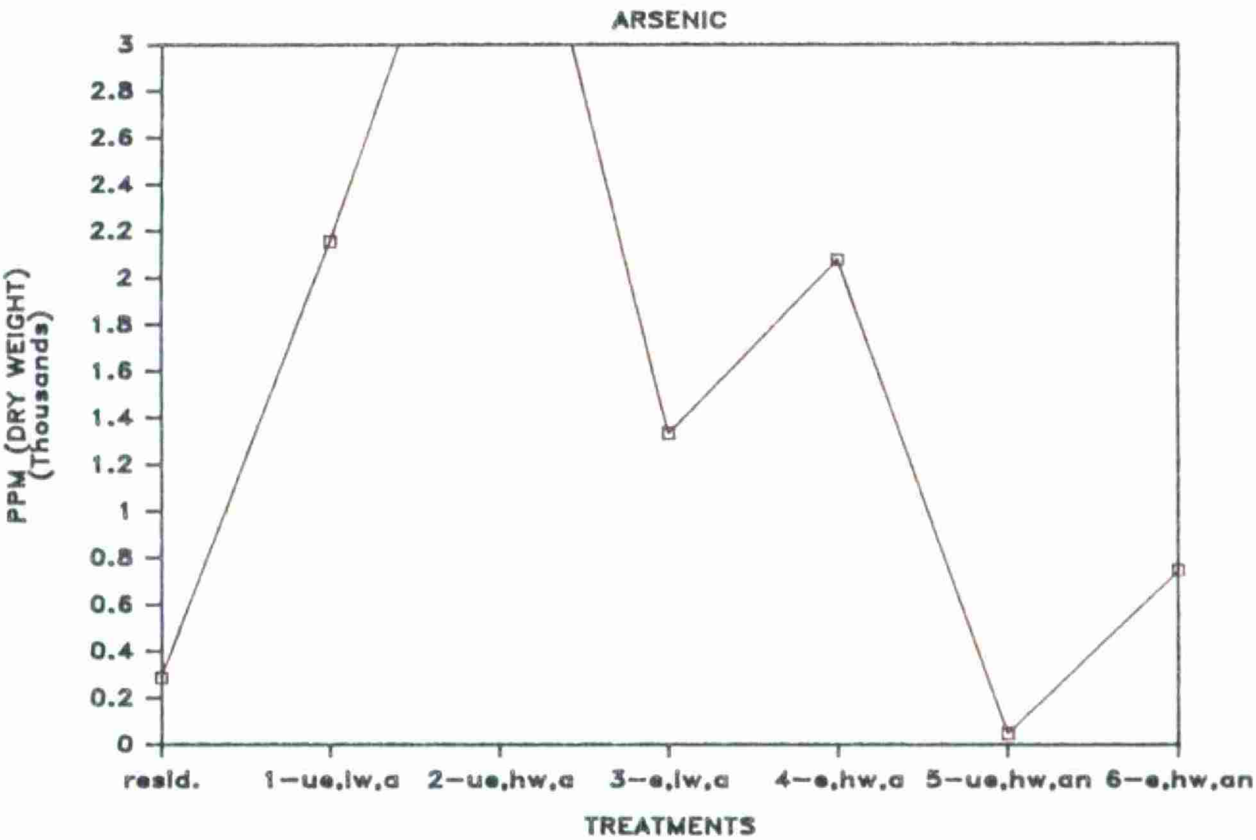
BIOLOGICAL UPTAKE OF HEAVY METALS



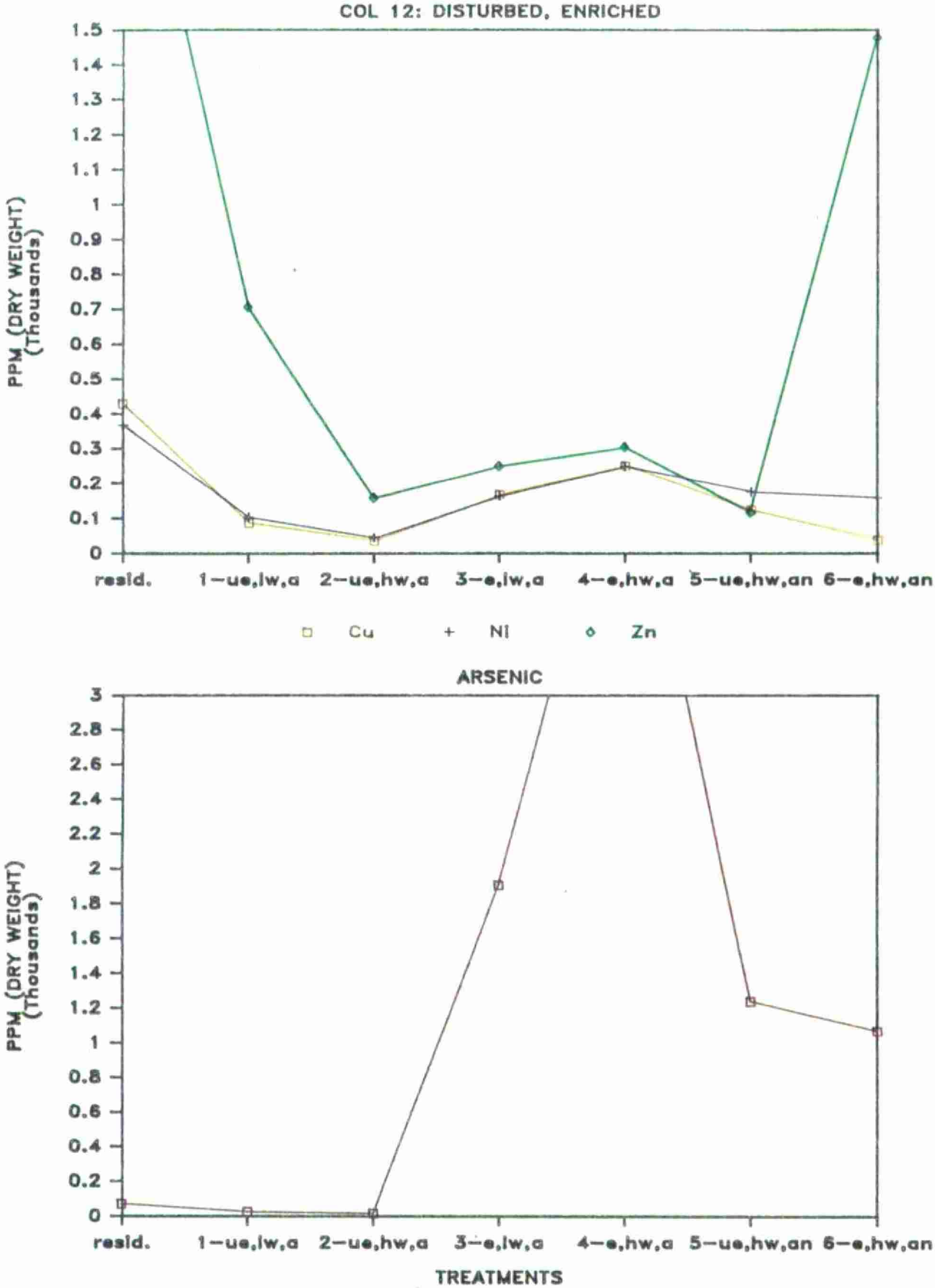


BIOLOGICAL UPTAKE OF HEAVY METALS





BIOLOGICAL UPTAKE OF HEAVY METALS

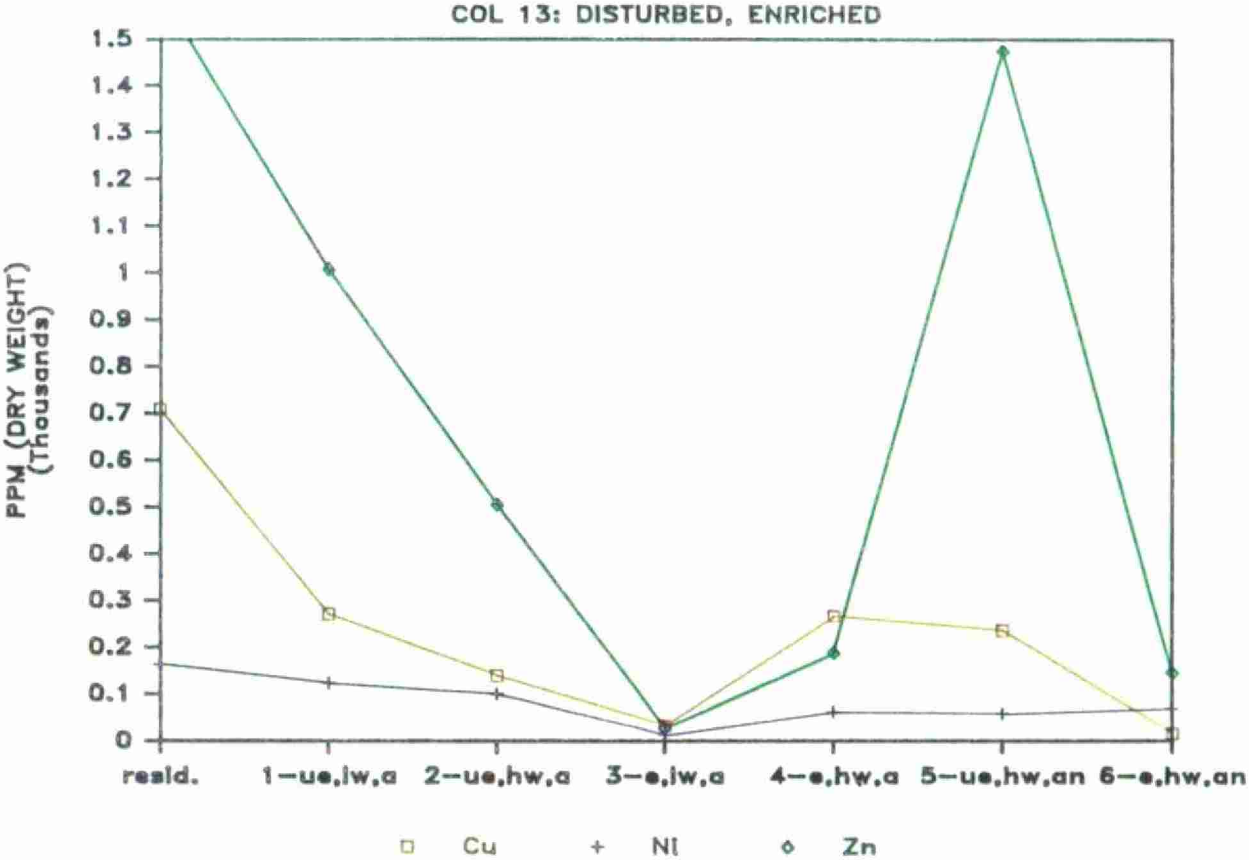


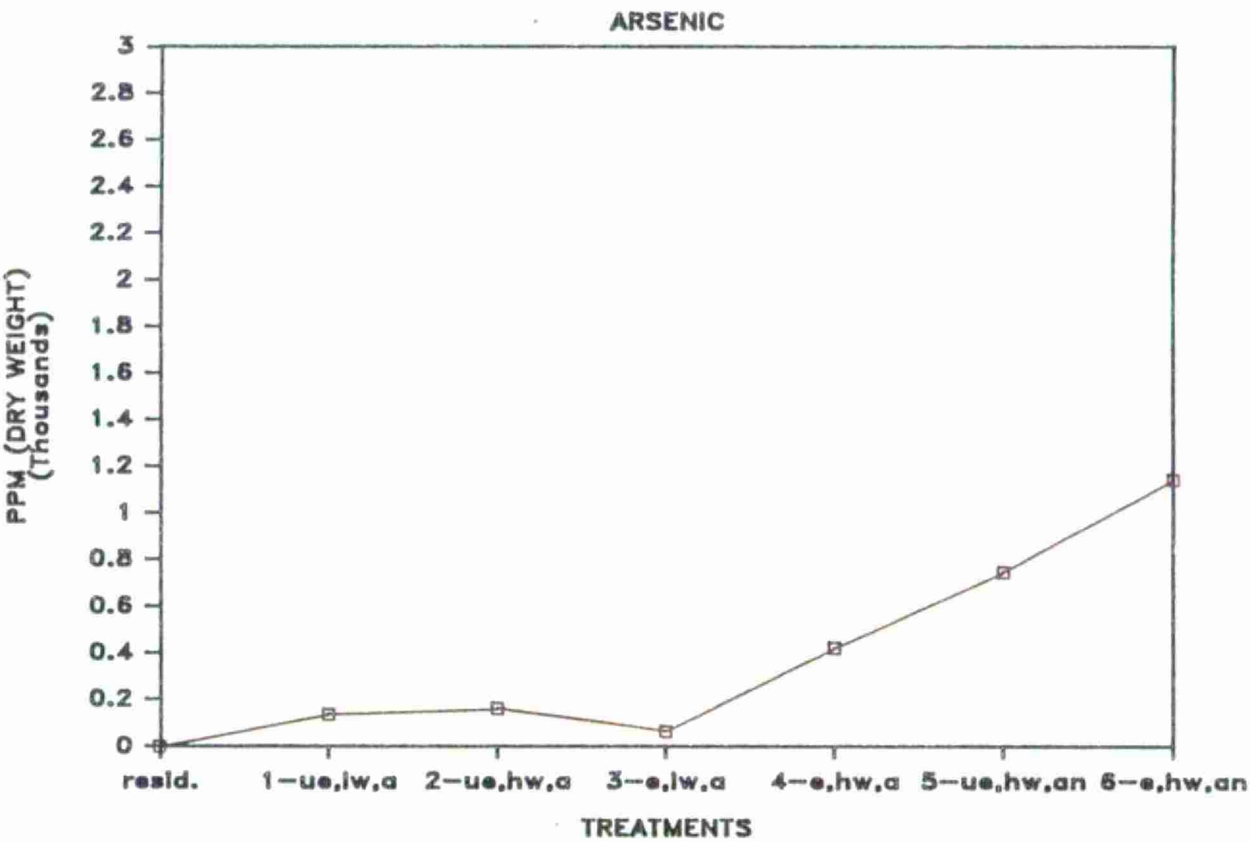
Heavy Metal Mobilization
and Bioavailability
Cobalt Mine Tailings

J E Hanna
Associates Inc.

Fig. A - 74

BIOLOGICAL UPTAKE OF HEAVY METALS





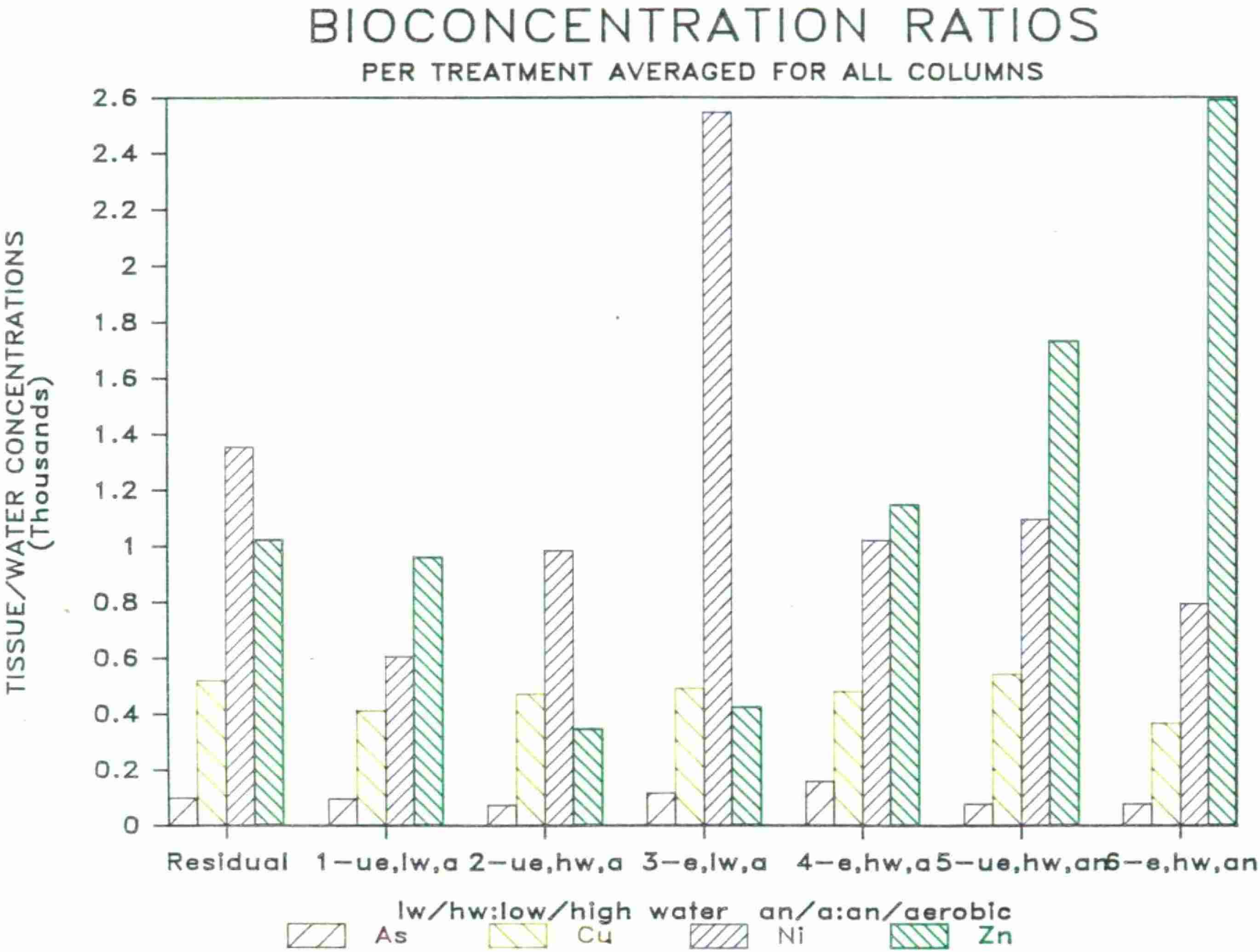


Fig. A-76

J E Hanna Associates Inc.

Heavy Metal Mobilization and Bioavailability Cobalt Mine Tailings

	DATE DUE	